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FINAL REPORT

SUPERCONDUCTING OXIDE FILMS FOR MULTISPECTRAL INFRARED SENSORS

A. I. Braginski and M. G. Forrester
Superconductor Materials and Electronics

January 1, 1988 to December 31, 1988

Westinghouse Electric Corporation
Research and Development Center
Pittsburgh, Pennsylvania 15235

AFOSR Contract No. F49620-88-C-0030

Research sponsored by the Strategic Defense Initiative Organization

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We have investigated optical detection in epitaxial and granular films of $YBa_2Cu_3O_{7-\delta}$, at wavelengths of 0.63, 3.39, and 10.6 µm, at temperatures from 4.2K to 100K. Epitaxial films, and granular films fabricated at Westinghouse, exhibit an optically-induced voltage shift, δV, which is proportional to the temperature derivative of the sample dc resistance at the same bias current. Granular films provided by the University of Texas, which exhibit "semiconducting" resistive behavior, exhibit a response which deviates from dR/dT, but which can be explained in terms of the temperature dependence of the film thermal conductance. The response time of all films is long and strongly wavelength dependent, varying from of order microseconds at 0.63 µm to tenths of a second at 3.39 µm. Our results indicate that all these films exhibit only bolometric or thermal detection, with no evidence for quantum or non-equilibrium effects in this temperature range. For 0.63 µm radiation, mechanically chopped at 725 Hz, measurements of a 10 × 90 µm epitaxial bridge yield a bolometric

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1. FINAL REPORT, SUPERCONDUCTING OXIDE FILMS FOR MULTISPECTRAL INFRARED SENSORS

January 1, 1988 to December 31, 1988

AFOSR Contract Number F49620-88-C-0030

M. G. Forrester, M. Gottlieb, J. Talvacchio, J. R. Gavaler, and
A. I. Braginski

2. ABSTRACT

We have investigated optical detection in epitaxial and granular films of $YBa_2Cu_3O_{7-\delta}$, at wavelengths of 0.63, 3.39, and 10.6 μm, and at temperatures from 4.2K to 100K. Epitaxial films, and granular films fabricated at Westinghouse, exhibit an optically induced voltage shift, δV, which is proportional to the temperature derivative of the sample dc resistance at the same bias current. Granular films provided by the University of Texas, which exhibit "semiconducting" resistive behavior, exhibit a response which deviates from dR/dT, but which can be explained in terms of the temperature dependence of the film thermal conductance. The response time of all films is long and strongly wavelength dependent, varying from on the order of microseconds at 0.63 μm to tenths of a second at 3.39 μm. Our results indicate that *all* these films exhibit only bolometric or thermal detection, with no evidence for quantum or nonequilibrium effects in this temperature range. For 0.63 μm radiation, mechanically chopped at 725 Hz, measurements of a 10 $\times$ 90 μm epitaxial bridge yield a bolometric responsivity of approximately 4×10^3 V/W, and a detectivity D^* of more than 10^8 cm $\sqrt{Hz}$/W. Granular films biased above their critical current are found to exhibit two-level switching noise, resulting in Lorentzian deviations from an otherwise "1/f" noise spectrum. The results suggest that the use of controlled high-temperature superconducting weak links is a more promising route to the development of a fast, multispectral, superconducting infrared detector.

3. OBJECTIVES

The objectives and Tasks of this program were:

1. Design, construct, and demonstrate operation of a test apparatus for the evaluation of superconducting oxide IR detectors.
2. Investigate correlations between the oxide film geometry, morphology, and granularity, and its optical (IR) and superconducting properties.
3. Compare the IR superconducting sensor performance with that of known semiconductor IR sensors, and determine technical feasibility.

4. ACCOMPLISHMENTS

4.1 PREAMBLE

The research reported here was done under a program supported by AFOSR/SDIO which began in January 1988. The program was to have been for two years but was discontinued in December 1988 due to lack of funds. For this reason Tasks 2 and 3 were not fully completed. However, the results obtained through this program form the base for a new SDIO program to begin in February 1989, which will form the HTS materials base for the development of a HTS/LTS infrared focal plane array (IR FPA). The tasks of the new program are presented in Section 4.6.

Most of the results obtained in this program have been published in three papers, which are listed in Section 5. These articles are reproduced and attached to this report as appendices one through three. Relevant references to non-Westinghouse work can be found in these appendices. Only a summary of accomplishments is given below, since the factual documentation of results obtained under this program is given in the appendices.

4.2 CRYOGENIC OPTICAL TEST APPARATUS

A cryogenic optical testing apparatus has been brought into operation, based on a "Hi-Tran" open-cycle helium refrigerator built by R. G. Hansen and Associates. The apparatus has a temperature range from 350K to 4.2K and electrical access for four-point measurement of two samples, as well as for dual temperature sensors. Optical access is provided by interchangeable windows of MgF, KRS-5, and CsI, providing a wavelength coverage of 0.1 to 70 μm. Radiation sources used in the course of this work included lasers of wavelength 0.63, 3.39, and 10.6 μm, as well as a black-body source.

Instrumentation for the apparatus includes a dynamic signal analyzer, with frequency range from 10^{-3} Hz to 100 kHz, for characterization of the noise properties of HTS detectors.

We have developed techniques for patterning films of $YBa_2Cu_3O_7$ (YBCO) into geometries suitable for detector studies, such as microbridges and meander paths. As a result of progress made under the AFOSR program "Superconducting Electronic Film Structures," Contract No. F49620-88-C-0039, we were able to produce bilayers consisting of sputtered YBCO with an evaporated gold overlayer, in an entirely in-situ process, resulting in unmeasurably low contact resistance between the gold and YBCO ($R < 4 \times 10^{-10}$ Ω-cm^2). This was of importance to avoid heating effects and excess noise which can result from the usual high-resistance contacts to YBCO. We used a photolithographic process in which the gold was patterned into a contact geometry by reactive-ion etching with a mixture of Freon-12 and argon, and the YBCO film subsequently patterned by Ar-ion milling. Using these techniques we were able to fabricate lines as narrow as 10 μm in epitaxial films, with no appreciable degradation in the superconducting properties. Granular films, on the other hand, typically suffered a T_c degradation of 10 to 20K under such processing.

4.3 FILM PROPERTIES

We have investigated the optical response of both epitaxial and granular YBCO films in the visible and infrared. Epitaxial films were deposited on $SrTiO_3$, typically to a thickness of 0.35 μm, and were post-annealed in oxygen, either in-situ or ex-situ. The films had the crystallographic c-axis in the film plane and consisted of a random mosaic pattern of crystalline grains with perpendicular c-axes. Transition temperatures for these films ranged from 35K to 85K, depending on the stoichiometry, with the resistance above the transition always "metallic," that is, increasing monotonically with increasing temperature.

The granular films were deposited under the same conditions, onto sapphire substrates with 0.4 to 0.5 μm thick BaF_2 buffer layers. For these films T_c's (R=0) were as high as 70K. Micrographs of the granular films revealed islands of needle-shaped grains of YBCO, interspersed with a highly Ba-enriched phase, probably mostly BaF_2. Regardless of the T_c value of these films, the resistive behavior was again metallic.

Measurements of transport critical current density vs. magnetic field, $J_c(H)$, revealed an important difference between the epitaxial and granular films. As illustrated in Figure 4.1, the epitaxial films had zero-field J_c's on the order of 10^5 A/cm^2, with a relatively weak magnetic field dependence. In contrast, the granular films exhibited much lower zero-field J_c's, typically on the order of 100 A/cm^2, with a very strong field dependence at low fields. These behaviors indicated that the grains in our epitaxial films were strongly coupled, while those in the granular films were weakly coupled. The presence of weak grain boundaries in granular films suggested that such films might be more likely to exhibit a nonequilibrium optical response, which depends on optical pair-breaking to produce phase-slips, and hence a voltage, across such a link.

In addition to the films produced in our laboratory, we have characterized the optical response of granular films provided by Prof. A. de Lozanne and R. M. Silver of the University of Texas at Austin. These films were deposited on sapphire and were crystalline as deposited. The key difference in their characteristics for our purposes was that they exhibited "semiconducting" resistive behavior, with resistance decreasing monotonically with increasing temperature above the transition. Such films may have intergrain weak links of a different character from the Westinghouse granular films, and it has been suggested by other workers in the field that such a resistive profile is a prerequisite for observing nonequilibrium optical response.

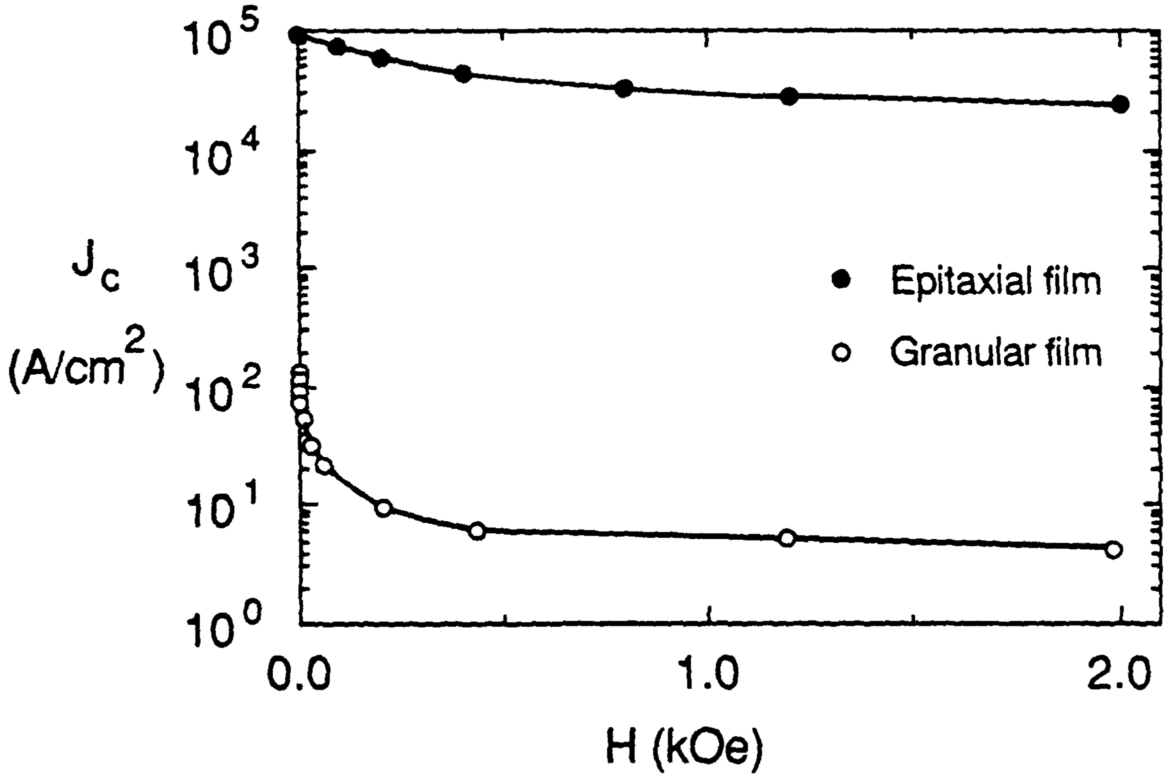


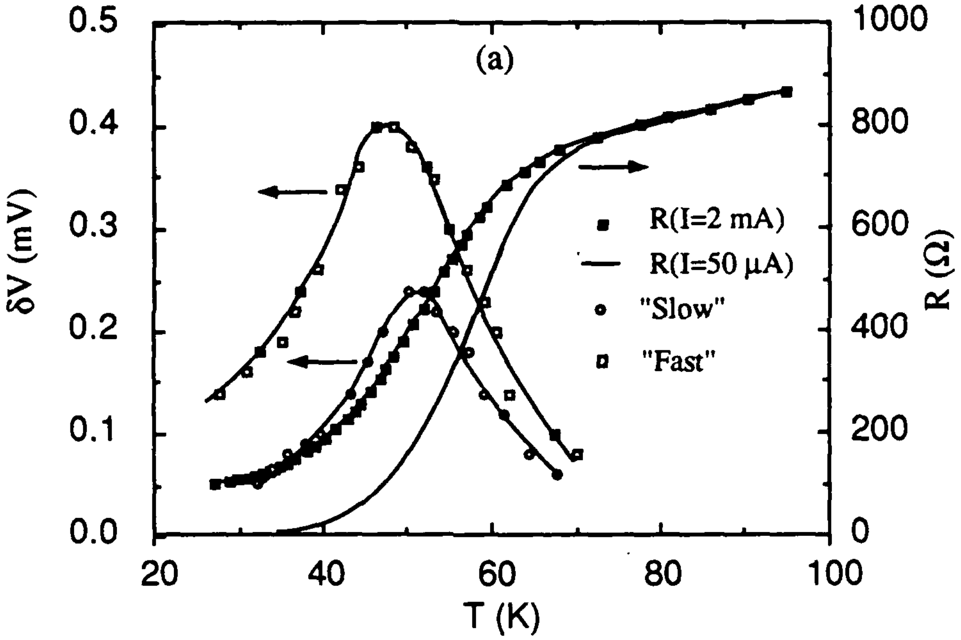
Figure 4.1 - Transport critical current density vs. magnetic field at 4.2K, for epitaxial (closed symbol) and granular (open symbol) films. The granular film shows a low J_c and strong field dependence at low fields, indicating that its grains are weakly coupled.

4.4 OPTICAL RESPONSE

We have studied the optical response of the three types of film to chopped laser radiation of wavelengths 0.63, 3.39 and 10.6 μm, typically at chopping frequencies up to 1 kHz. The characteristic time for the optical response of these films was found to be long, from several microseconds to several tenths of a second, depending on the wavelength. For example, the response to 0.63 μm radiation showed a "fast" turn-on in several microseconds in a 10 $\times$ 90 μm bridge, followed by a "slow" increase with characteristic time of about one millisecond. In contrast, the responses to 10.6 and 3.39 μm radiation showed only a single time constant on the order of milliseconds and several tenths of a second, respectively. We have also observed that these time scales are longer in a longer sample, such as a meander pattern. The exact origin of the different response times at the various wavelengths is currently unknown but is presumably due to the absorption of the different wavelengths by different portions of the film/substrate combination.

Figure 4.2(a) shows the temperature dependence of the fast and slow optical response of a 10 $\times$ 90 μm epitaxial bridge, to 0.63 μm radiation chopped at 725 Hz. Also shown is the sample dc resistance, both for low bias current and the same bias current used for the optical response measurement. One sees that, for a given bias current, both components of the optical response peak where R(T) is steepest, and fall off monotonically for higher and lower temperatures. This suggests that the response is bolometric, that is, the radiation is simply heating the sample and thereby raising its resistance.

Figure 4.2(b) shows the bias current dependence of the fast response of Figure 4.2(a). One sees that, for sufficiently high temperature, the response shows a peak as a function of bias current, a behavior which some workers have suggested is a signature of a nonequilibrium effect. However, such behavior is easily explained in terms of a bolometric effect, where the voltage shift δV is given by



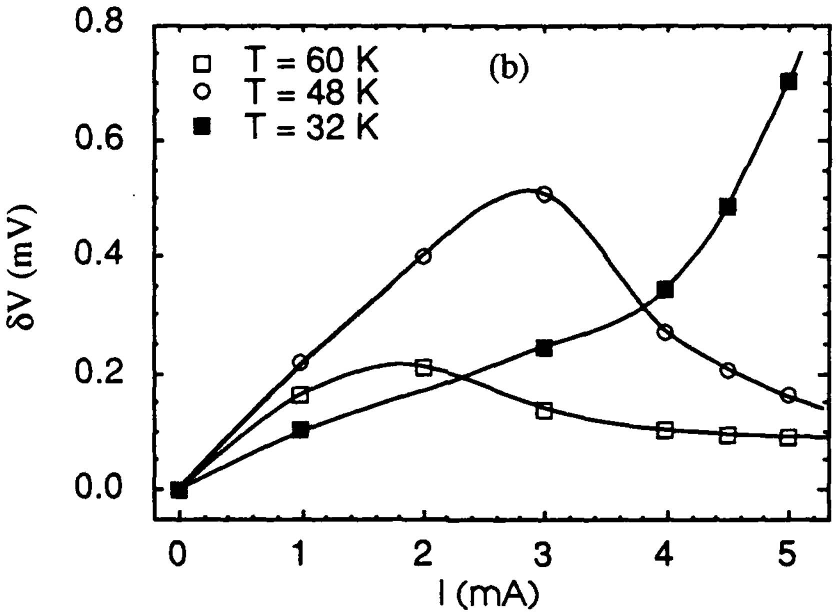


Figure 4.2 - (a) Temperature dependence of fast and slow responses, δV, of a 10 × 90 μm epitaxial bridge, for $\lambda = 0.63$ μm with corresponding R(T) curves. Both responses peak near the steepest part of the transition, independent of current, indicating that they are bolometric. Also shown is a low-current R(T) showing $T_c \lesssim 35K$ for this sample.
(b) Current response of the fast response of (a). The peak in δV observed at higher temperatures can be explained by current-induced broadening of the transition, which leads to a lower dR/dT and hence a lower bolometric responsivity.

$$\delta V = \frac{dV}{dT}\,\delta T = I_B\,\frac{dR}{dT}\,\delta T\ , \tag{4.1}$$

with I_B the bias current and δT the temperature rise due to the radiation. As I_B increases the signal first increases linearly, but at higher currents dR/dT decreases as the transition is broadened by the finite current, which exceeds the critical current over a broad temperature range. For sufficiently high currents in fact, dR/dT, and thus δV, would be on the order of its value above the transition onset temperature, which is much smaller than the peak value in the transition regime.

Figure 4.3 shows the temperature dependence of the response of a granular film to 0.63 μm radiation, as well as dR/dT at the same bias current. Here one sees even more convincingly that δV follows dR/dT very closely, as predicted by Equation 4.1.

The optical response of the Texas granular films appears superficially different from that of the Westinghouse films. Figure 4.4 shows $\delta V(T)$ at two bias currents, along with the behavior of dR/dT at the same bias current. One sees significant deviations from the behavior of Equation 4.1, with δV deviating strongly from dR/dT at low temperatures. For sufficiently high bias current one sees that the response actually increases with decreasing temperature below about 40K. Similar data have been reported by workers at Hughes, who suggested that the rise at low temperature might be due to nonequilibrium effects. We suggest an alternative, much simpler explanation -- that the thermal conductance, G, linking the HTS film to the heat sink (perhaps that of the film itself) has a temperature dependence in this regime. This would lead to the temperature rise δT in Equation 4.1 being temperature dependent, with δT proportional to 1/G. In fact, data in the literature (see Appendix 3, Reference 13) indicate that the thermal conductance of YBCO falls off rapidly with decreasing temperature below about 40K, which would lead to an increase in δT and hence in δV with decreasing

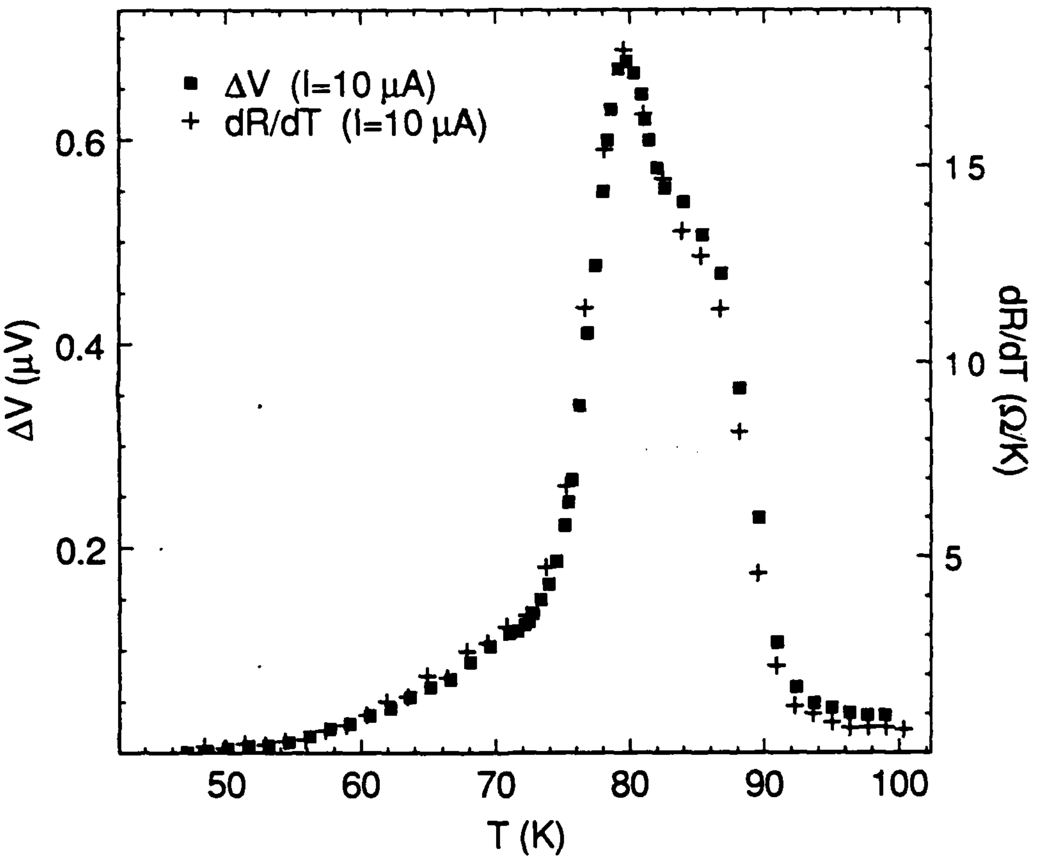


Figure 4.3 - Response of a granular film to 0.63 μm radiation, compared to dR/dT. The data indicate that the radiation is simply heating the sample by a fixed amout, δT, independent of temperature.

OPTICAL RESPONSE OF YBCO FILMS WHICH ARE "SEMICONDUCTING" FOR $T > T_c$

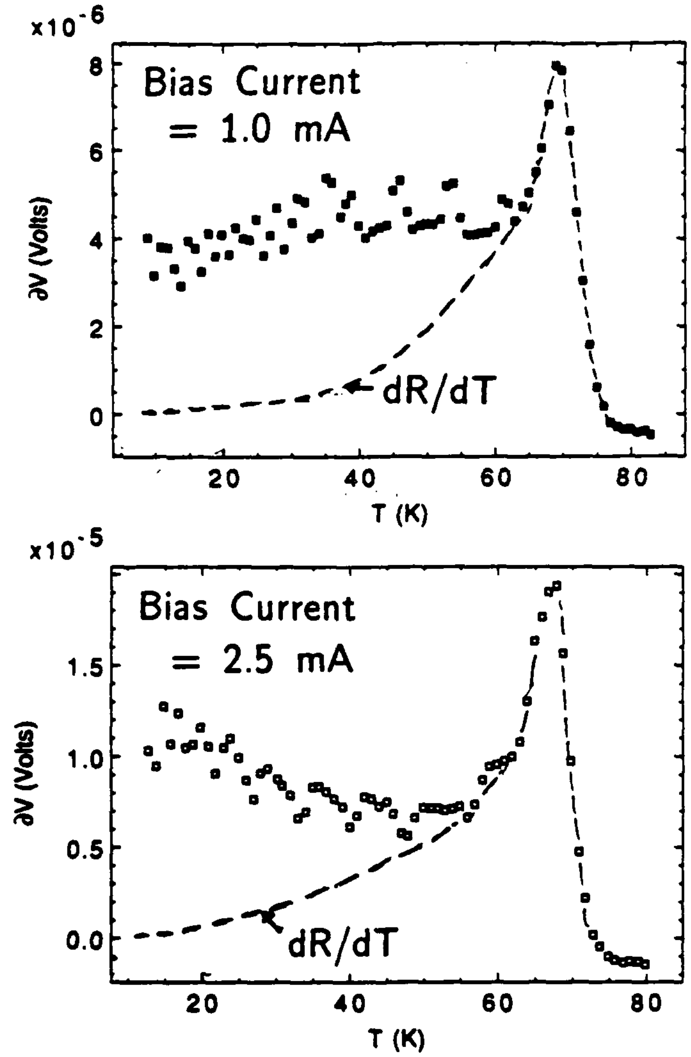


Figure 4.4 - Response of the University of Texas granular films to 0.63 μm radiation, compared to dR/dT. The disparity between δV and dR/dT at low temperatures can be explained by the temperature dependence of the thermal conductance of the HTS film.

temperature, consistent with our data. Thus, our interpretation is that this effect is again bolometric, as in the Westinghouse films.

Our interpretation of the observed effects as being bolometric is reinforced by the results of numerical simulations of arrays of weak links (see Appendix 3). We have used a model in which the critical currents of a series array of 100 weak links have a truncated gaussian distribution, whose standard deviation, σ, is a specified fraction of the average critical current. By incorporating into the model data from the literature on the thermal conductance of YBCO, and choosing the value of σ so that the experimental and simulated current-voltage characteristics are similar, we have generated data for the bolometric effect vs. temperature which are in rather good qualitative agreement with the data on the Texas films. An example is shown in Figure 4.5, which compares well with the data of Figure 4.4 at 2.5 mA.

The highest measured bolometric responsivity, 4×10^3 V/W, was for a 10×90 μm epitaxial bridge with a corresponding detectivity $D^* \approx 10^8$ cm $\sqrt{Hz}$/W. This was for 0.63 μm radiation chopped at 725 Hz, with the noise measured in a 100 Hz bandwidth at 1 kHz, at a temperature of about 30K. This is to our knowledge the highest responsivity and detectivity reported to date for a YBCO film.

With regard to noise, we have found that the voltage noise in a current-biased granular microbridge is typically an order of magnitude larger than that of an epitaxial bridge at the same voltage level. In addition, for certain values of the bias voltage (actually the bias current times the resistance) one observes marked two-level switching or "telegraph" noise. Detailed measurements of the noise spectral density, Sv(f), from 1 Hz to 100 kHz in granular films revealed a generally "1/f" behavior, but with well-defined features which can be well fit by Lorentzian spectra characteristic of such telegraph noise.

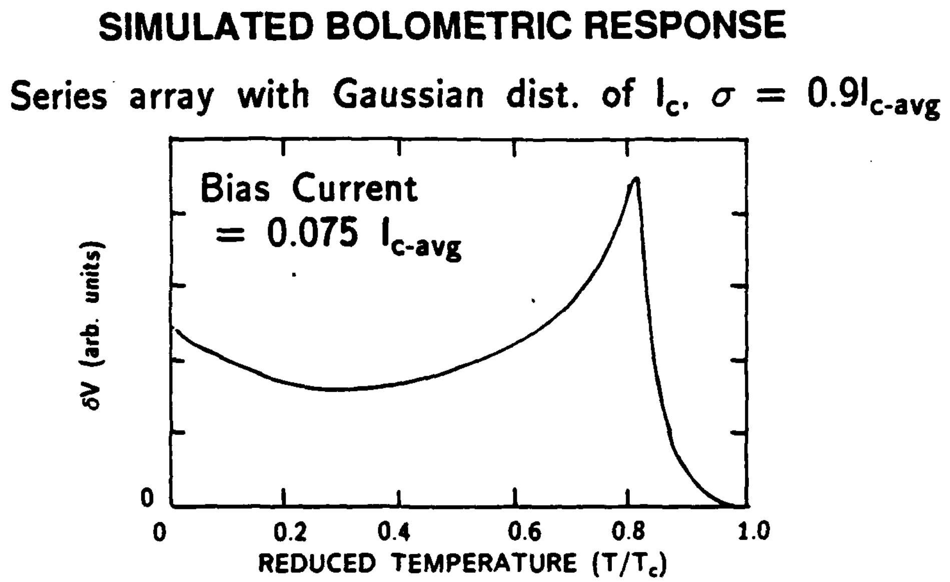


Figure 4.5 - Simulation of the bolometric response of a series array of 100 weak links, incorporating a temperature dependent thermal conductance to the heat sink. Using published data for the thermal conductance of YBCO, and array parmameters consistent with the experimental current-voltage characteristics of HTS films, one obtains qualitative agreement with the data of Figure 4.4, at 2.5 mA.

4.5 COMPARISON OF HTS IR DETECTOR PERFORMANCE WITH SEMICONDUCTOR DETECTORS

Due to the premature termination of the program, and to the fact that a nonequilibrium optical detection mechanism was not observed during the period of performance, the third task was not addressed in any depth. On general grounds one can say that the observed bolometric response is insufficiently sensitive, as well as too slow, for state-of-the art FPA applications. Such applications require a quantum (rather than thermal) detector, based on an intrinsically fast nonequilibrium detection mechanism.

4.6 DISCUSSION

It is theoretically expected that HTS films should exhibit a nonequilibrium response to above-gap radiation. Such an effect depends on the existence of quasiparticles of character similar to those in conventional superconductors, and existing data provide no reason to doubt the existence of such quasiparticles. Our failure to observe the nonequilibrium response observed in the low-T_c oxide superconductor $BaPb_{1-x}Bi_xO_3$ (BPB) suggests that this mechanism is more subtle than anticipated, perhaps depending on some particular quirk of the microstructure of BPB films.

A possible explanation for the lack of nonequilibrium detection is that the distribution of critical currents in the intergrain junctions is too broad in YBCO, so that, at a given bias current, very few of the junctions are biased such as to be sensitive to the radiation or "photoactive." Most of the junctions may be biased either into the normal state or below their critical currents. This suggests that one should abandon the approach based on granular HTS films with naturally occurring weak links, and fabricate weak link arrays with more narrow distributions of critical currents. Such an approach will be emphasized in the 1989 SDIO-supported program on HTS IR detectors, where we will investigate the optical response of granular films with artificially altered grain boundaries, and of series arrays of discrete, planar, HTS

S-N-S junctions. The tasks for that program are detailed in the next section.

On the question of noise, it is clear that as-deposited granular films will not exhibit high detectivity, regardless of the existence of the desired nonequilibrium detection mechanism, because of the excess 1/f and telegraph noise associated with the grain boundaries. It may, however, be possible to reduce this noise by tailoring the properties of the grain boundaries, for example, by decorating them with a nonreactive normal metal to eliminate trap states in the intergrain barriers and to modify the flux-trapping characteristics. Such an approach will be an important part of the 1989 program.

4.7 TASKS OF THE 1989 SDIO-SUPPORTED PROGRAM: "HIGH TEMPERATURE SUPERCONDUCTING DETECTORS FOR MULTISPECTRAL INFRARED SENSORS"

The 1989 SDIO-supported program, building on the base formed by the results of the 1988 program, will seek to determine the feasibility of using HTS films to detect IR radiation by optically induced nonequilibrium effects, and to provide HTS detectors for the FPA program. To these ends the tasks of the program will be as follows:

1. Determine the feasibility of nonequilibrium IR detection mode in modified granular HTS films.
2. Determine the feasibility of nonequilibrium IR detection mode in discrete S-N-S junction devices and series arrays patterned from epitaxial HTS films.
3. Measure the noise spectral density in the IR detectors of Tasks 1 and 2, and correlate noise with superconducting, normal state, and optical properties.
4. Measure the reflectance and transmittance of HTS films and correlate with film morphology and carrier density.
5. Fabricate, test, and deliver optimized HTS detectors for the Westinghouse FPA.

5. CONCLUSIONS

The following conclusions can be derived from the results obtained during this one-year period of performance:

1. Task one was completed. A test apparatus was constructed for the evaluation of superconducting oxide IR detectors.
2. The objectives of Task two were attained in part. It was found that:
   (a) Random weak-link arrays based on HTS films do not exhibit a measurable quantum response to visible or IR radiation. The observed response is bolometric.
   (b) Noise levels in granular HTS films, both "1/f" and telegraph, severely limit the usefulness of such films for detector applications.
3. Task three was not specifically addressed, since the lack of a useful quantum response precludes a meaningful comparison with the performance of semiconductor quantum detectors.
4. Based on one year of performance our understanding has advanced to the point where a new, more focussed approach has been formulated for future work.

6. PUBLICATIONS

1. "Photodetection with High-T_c Superconducting Films," J. Talvacchio, M. G. Forrester, and A. I. Braginski, to appear in Science and Technology of Thin-Film Superconductors, edited by R. McConnell and S. A. Wolf, Plenum, New York, 1989.
2. "Optical Response of Epitaxial and Granular Films of $YBa_2Cu_3O_{7-\delta}$ at Temperatures from 25K to 100K," M. G. Forrester, M. Gottlieb, J. R. Gavaler, and A. I. Braginski, to appear in the proceedings of the 1988 Applied Superconductivity Conference, IEEE Trans. Magn. MAG-25, 1989.
3. "Optical Response of Epitaxial Films of $YBa_2Cu_3O_{7-\delta}$," M. G. Forrester, M. Gottlieb, J. R. Gavaler, and A. I. Braginski, Appl. Phys. Lett. 53, 1332 (1988).

7. PERSONNEL

A. I. Braginski - Principal investigator
J. Talvacchio - Co-principal investigator

M. G. Forrester
M. Gottlieb
J. R. Gavaler

8. COUPLING ACTIVITIES*

1. "Optical Response of Epitaxial YBCO Films," M. G. Forrester, M. Gottlieb, J. R. Gavaler, and A. I. Braginski, Contributed presentation at the March Mtg. of the American Physical Society, New Orleans, March 1988.

2. "In-Situ Fabrication, Processing, and Characterization of Superconducting Oxide Films," A. I. Braginski, M. G. Forrester, J. Talvacchio, J. R. Gavaler, and M. A. Janocko, SPIE Conference 948 on High-T_c Superconductivity: Thin Films and Devices, Newport Beach, California, March 1988.

3. "Epitaxial Growth and In-Situ Analysis of Thin Films for Superconductive Electronics," J. Talvacchio, Seminar at IBM T. J. Watson Research Center, May 1988.

4. "Optical Response of Epitaxial and Granular Films of $YBa_2Cu_3O_{7-\delta}$ at Temperatures from 25K to 100K," M. G. Forrester, M. Gottlieb, J. R. Gavaler, and A. I. Braginski, Contributed presentation at the Applied Superconductivity Conference, San Francisco, August 1988.

5. "Materials for High-Temperature Superconducting Electronics," J. Talvacchio, U. of Akron Physics Department Colloquium, Akron, September 1988.

6. "Properties of Surfaces and Interfaces of High-T_c Superconductor Films for Electronic Applications," J. Talvacchio, M. G. Forrester, A. I. Braginski, J. R. Gavaler, G. R. Wagner, and J. Greggi, Electrochemical Society Mtg., Symposium on High-Temperature Superconductor Technologies, Chicago, October 1988.

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* Speaker is underlined.

7. "Photodetection with High-T_c Superconducting Thin Films," J. Talvacchio, M. G. Forrester, and A. I. Braginski, SERI Superconducting Thin Film Conference, Colorado Springs, November 1988.

8. "Properties of Surfaces and Interfaces of High-T_c Superconductor Films for Electronic Applications," J. Talvacchio, M. G. Forrester, A. I. Braginski, J. R. Gavaler, G. R. Wagner, and J. Greggi, International Superconductor Applications Convention, San Francisco. January 1988.

(Items 2, 3, 5, 6, and 8 were general presentations of Westinghouse HTS film research which featured results on optical detection.)

APPENDICES

Appendix 1: "Optical Response of Epitaxial Films of $YBa_2Cu_3O_{7-\delta}$."

Appendix 2: "Optical Response of Epitaxial and Granular Films of $YBa_2Cu_3O_{7-\delta}$ at Temperatures from 25K to 100K."

Appendix 3: "Photodetection with High-T_c Superconducting Films."

Optical response of epitaxial films of $YBa_2Cu_3O_{7-\delta}$

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We present the results of measurements of optical detection in epitaxial films of $YBa_2Cu_3O_{7-\delta}$, at wavelengths of 0.63 and 10.6 μm. In contrast to the behavior observed in granular materials, these films appear to show no evidence of nonequilibrium response (breaking of Cooper pairs by photons), but only a bolometric effect (heating of the sample by radiation) in the resistive transition regime. This suggests that epitaxial films do not contain intrinsic links weak enough to be modulated by the incident radiation. For 0.63 μm radiation, mechanically chopped at 725 Hz, measurements of a 10 μm $\times$ 90 μm bridge yield a bolometric responsivity of approximately 4×10^3 V/W, and a detectivity D^* of more than 10^8 cm Hz$^{1/2}$/W.

Since the discovery of high-temperature superconductors (HTS's) in 1986, there has been a great deal of interest in their technological application, both in electronics and in large scale applications such as magnets and energy transmission. While processing of bulk conductors is still at a rudimentary stage, thin-film fabrication is sufficiently advanced that some potential electronic applications may now be evaluated. One of the most promising of these is the use of HTS films as broadband optical and infrared sensors.

Optical detection has previously been demonstrated in *granular* films of both low- and high-temperature superconductors, including $BaPb_{1-x}Bi_xO_3$,[1] NbN/BN,[2] and $YBa_2Cu_3O_{7-\delta}$ (YBCO).[3] The detection mechanism in such films, for photons with energies above the gap, is thought to be an optically induced phase slip process in the relatively weak "boundary Josephson junctions" (BJJ's) between the grains. Photons with energies above the gap break Cooper pairs, producing a nonequilibrium population of quasiparticles, and thereby diminishing the critical current of the BJJ's. A film biased near its critical current will thus exhibit a voltage change across the BJJ's upon irradiation, with a characteristic time scale determined by the quasiparticle recombination time, which can be as short as 10^{-10} s in a strong coupling superconductor. BJJ's arranged in series may contribute coherently to the signal, but incoherently to the noise, so that the signal to noise ratio will go as $1/\sqrt{N_s}$, where N_s is the number of junctions in series.[1]

In this letter we report the results of measurements of the optical response of *epitaxial* YBCO films, at wavelengths of 0.63 and 10.6 μm.[4] Although such films do not exhibit classic granular behavior, with strongly superconducting grains and weak intergrain Josephson coupling, they could potentially contain an intrinsic weak link structure due to, for example, weakly coupled Cu-O planes, defects such as stacking faults,[5] or boundaries between single-crystal domains of different orientation. If this were the case then, in a sample of a given size, N_s might be much higher than in a granular film, making the signal larger for a given incident flux and improving the signal to noise ratio. In addition, epitaxial films have the advantage that they exhibit lower intrinsic noise than granular films,[6] so that one can expect higher detectivity.

Our fabrication procedure and details of film morphology have been reported elsewhere,[7,8] and only a brief summary will be given here. Films were deposited on single-crystal $SrTiO_3$ (100) and (110) substrates, by sequential magnetron sputtering from Y, Ba, and Cu sources, in oxygen partial pressures ranging from 3×10^{-6} to 3×10^{-4} Torr, and were typically 350 nm thick. Annealing was performed in an atmosphere of oxygen, either entirely *in situ*, or partially *in situ*. Of relevance here is that for films both annealed and coated with gold *in situ*, we were able to achieve contact resistances below our measurement sensitivity of 4×10^{-10} Ω cm^2.[8]

The resulting films were epitaxial, with the *c* axis in the film plane, and consisting of a random mosaic pattern of crystalline grains with perpendicular *c* axes. Measurements of transport critical current density versus magnetic field, $J_c(H)$, in films patterned into 25-μm-wide bridges suggest that these grains are, however, strongly coupled, so that the films do not exhibit the "granular" type behavior characteristic of weakly coupled grains. Specifically, transport J_c's in zero field at 4.2 K were typically 2×10^5 A/cm^2, consistent with transport along the *c* direction in single crystals,[9] and typically decreased by a factor of 3 in a field of 20 kOe. This is in sharp contrast to granular materials, which typically show a sharp drop in $J_c(H)$ at fields of less than 1 kOe.[10]

For this work we deliberately chose to measure films of lower quality than our best films, in the belief that they should be more likely to exhibit intrinsic weak link behavior, and hence higher sensitivity to radiation. Thus, although our best films have T_c (zero resistance) of 85 K, those used in this study had $T_c \approx 35$–60 K. The films were patterned by conventional photolithography into 10 μm $\times$ 90 μm microbridges and, in one case, into a 25 μm $\times$ 22 mm meander line. For samples with gold overlayers the gold was first patterned by reactive ion etching, to form contact pads, and to define the area of superconducting films which would be exposed to radiation. For all samples the YBCO pattern was then defined by Ar ion milling at 200 V. Using this process we have found no appreciable degradation in superconducting properties for linewidths of 10 μm and larger. Figure 1 shows an example of a sample produced in this manner. The broad lines on the left and right are the gold-coated current bias

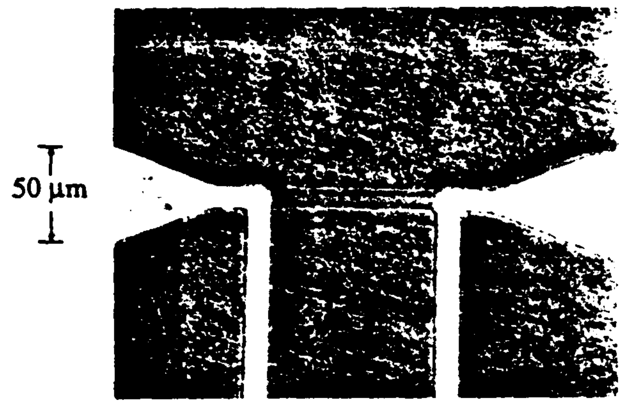

FIG. 1. Micrograph of an YBCO detector with gold-coated signal and bias lines. The $10\,\mu m \times 90\,\mu m$ photosensitive area is at center.

lines, while the narrower lines at the bottom are the voltage signal lines. The $10\,\mu m \times 90\,\mu m$ photosensitive area is at the center.

Our radiation sources were a 3 mW HeNe laser of wavelength $\lambda = 0.63\,\mu m$, and a 7 W CO_2 laser with $\lambda = 10.6\,\mu m$. The CO_2 laser beam was attenuated to approximately 40 mW by reflection off a NaCl crystal. Both lasers were mechanically chopped, typically at frequencies of several hundred hertz.

Our experimental procedure was to bias the sample at a fixed current at or above its critical current, and observe the ac voltage response to radiation, δV, either directly on an oscilloscope, or with a lock-in amplifier, as a function of temperature T and bias current I. The response of a $10\,\mu m$ bridge to $0.63\,\mu m$ radiation, chopped at 725 Hz, is shown in Fig. 2, and exhibits two characteristic time scales. Upon the turning on of the laser beam there is an initial fast rise in a time of order a microsecond, followed by a slow rise with time scale of order a millisecond. Although there is not always a sharp division between the two parts of the response, we have used an arbitrary but consistent criterion to separate the two, in order to study their temperature dependences independently, observing the signal directly on an oscilloscope.

Figure 3 shows the temperature dependence of both parts of the response (denoted "fast" and "slow") for one

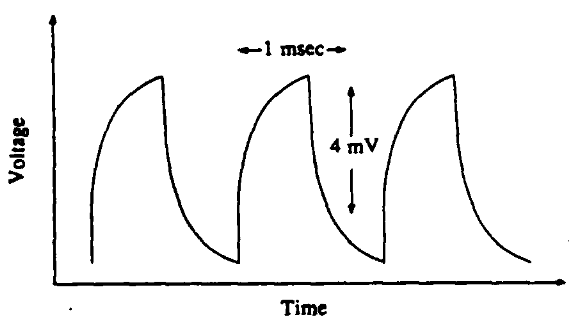

FIG. 2. Real-time response of a $10\,\mu m \times 90\,\mu m$ detector to $0.63\,\mu m$ radiation. In response to the turning on of the laser beam the sample voltage exhibits "fast" and "slow" components, with characteristic times of order 10^{-6} and 10^{-3} s, respectively.

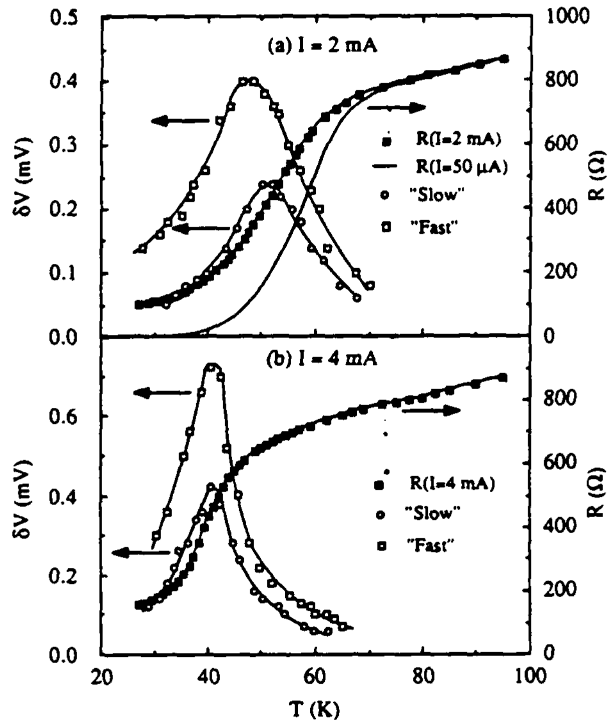

FIG. 3. Temperature dependence of fast and slow responses, δV, for $\lambda = 0.63\,\mu m$, at (a) $I = 2$ mA and (b) $I = 4$ mA, with corresponding $R(T)$ curves. Note that both responses peak near the steepest part of the transition, independent of current. Also shown in (a) is a low-current $R(T)$ showing $T_c \approx 35$ K.

sample at two different bias currents. Also shown for each current is the sample dc resistance versus temperature $R(T)$ at that current—effectively a current-dominated resistive transition curve. [Figure 3(a) also shows $R(T)$ measured at low currents for comparison.] One sees that the temperature dependences of the fast and slow responses are similar, and that for a given current both reach a maximum near the steepest portion of the $R(T)$ curve measured at that current. This is in contrast to the behavior seen in *granular* YBCO films, where the response peaked at the temperature where $R(T)$ went to zero, and was attributed to an optically induced phase slip process.[3]

The fact that the response to radiation has a maximum near where $R(T)$ is steepest suggests that the observed fast and slow responses are both bolometric in origin. That is, the radiation is simply heating the sample and thereby increasing its dc resistance. Superconducting bolometers have shown characteristic time constants from about 10 ns up to several milliseconds,[11] depending on the details of the material, the substrate, the sample mounting, etc., so that both of our observed time constants are within this range.

Clearly one can increase the detector's responsivity by increasing the bias current, subject to the limitation that, at the same time, the optimal temperature will decrease, and both the power dissipated and the shot noise due to the bias current will increase. Near the base temperature of our closed-cycle refrigerator (25 K) we have measured responsivities, for the fast response above, as high as 4×10^3 V/W.

From measurements of the sample noise we can estimate the detectivity $D^* = (A\,\Delta f)^{1/2}(r/V_N)$, where A is the

sample area, r the responsivity in volts per watt, V_N the rms noise voltage, and Δf the measurement bandwidth. For a 10 μm $\times 90$ μm detector with responsivity 4×10^3 V/W, noise measurements in a 100 Hz bandwidth at 1 kHz yielded $V_N \simeq 1\,\mu$V, which gives $D^* \simeq 10^8$ cm Hz$^{1/2}$/W. This value of D^* is 100 times larger than that reported for granular YBCO films,[3] but represents an intrinsically slower mechanism. We are currently investigating the nature and source of the noise which exhibits an approximately "$1/f$" power spectrum, and which may be partially extrinsic due to the measurement circuit, and partially intrinsic to the superconducting film.

Measurements of the response to 10.6 μm radiation yield a response similar to the slow response seen at 0.63 μm, with no apparent fast component. The temperature dependence is equivalent to that shown in Fig. 3 for 0.63 μm. Since the amplitude of the signal is obviously dependent on the chopping rate in this case, no direct comparison of responsivities for 0.63 and 10.6 μm can be made. However, a typical figure for a chopping frequency of 200 Hz is approximately 400 V/W, roughly consistent with the slow response seen at 0.63 μm in the same sample at a similar chopping frequency. The reason for the fast response at 0.63 μm and its absence at 10.6 μm is currently unknown but may be due to absorption of the different wavelengths by different portions of the film/substrate combination.

The fact that epitaxial films show no evidence of a nonequilibrium response to radiation suggests that they do not contain links weak enough to be significantly affected by the incident radiation.[12] This is consistent with the relatively high value of the transport J_c of these films, as well as with its magnetic field dependence. Although one might expect that epitaxial films could have intrinsic weak links which are sensitive to radiation, our results suggest the contrary. Our findings are also consistent with the work of Koch *et al.* at IBM, where polycrystalline YBCO films (with weak intergrain coupling) patterned into dc SQUID's exhibited modulation of critical current versus magnetic field, while epitaxial films did not. The difference has been attributed to the presence of weak grain boundaries in the former case and their absence in the latter.[13]

Our results suggest that development of a practical high-speed detector based on HTS thin films should emphasize either granular films, or artifically weakened epitaxial films. We are currently investigating both of these approaches.

We are pleased to acknowledge the assistance of H. Buhay in patterning the films. This work was supported by Air Force Office of Scientific Research/Strategic Defense Initiative Organization contract No. F49620-88-C-0030.

[1] Y. Enomoto and T. Murakami, J. Appl. Phys. **59**, 3807 (1986).
[2] M. Leung, U. Strom, J. C. Culbertson, J. H. Claassen, S. A. Wolf, and R. W. Simon, Appl. Phys. Lett. **50**, 1691 (1987).
[3] M. Leung, P. R. Broussard, J. H. Claassen, M. Osofsky, S. A. Wolf, and U. Strom, Appl. Phys. Lett. **51**, 2046 (1987).
[4] A preliminary report of these results was made at the APS March Meeting, New Orleans, 1988.
[5] Y. Enomoto, T. Murakami, M. Suzuki, and K. Moriwaki, Jpn. J. Appl. Phys. **26**, L1248 (1987).
[6] Unpublished presentation by J. Clarke, at the APS March Meeting, New Orleans, 1988.
[7] R. M. Silver, J. Talvacchio, and A. L. de Lozanne, Appl. Phys. Lett. **51**, 2149 (1987).
[8] J. R. Gavaler, A. I. Braginski, J. Talvacchio, M. A. Janocko, M. G. Forrester, and J. Greggi, in *High Temperature Superconductors II*, edited by D. W. Capone II, W. H. Butler, B. Batlogg, and C. W. Chu (Materials Research Society, Pittsburgh, 1988), p. 193.
[9] T. K. Worthington, W. J. Gallagher, and T. R. Dinger, Phys. Rev. Lett. **59**, 1160 (1987).
[10] J. W. Ekin, A. J. Panson, A. I. Braginski, M. A. Janocko, M. Hong, J. Kwo, S. H. Liou, D. W. Capone II, and B. Flandermeyer, in *Proceedings of the Symposium on High Temperature Superconductors*, edited by D. U. Gubser and M. Schluter (Materials Research Society, Pittsburgh, 1987), p. 223.
[11] See, for example, K. Rose, C. L. Bertin, and R. M. Katz, in *Applied Superconductivity*, edited by Vernon L. Newhouse (Academic, New York, 1975), Vol. I, Chap. 4.
[12] Similar conclusions were reported by Y. Enomoto, T. Murakami, and M. Suzuki, in Physica C **153-155**, 1592 (1988).
[13] R. H. Koch, C. P. Umbach, M. M. Oprysko, J. D. Mannhart, B. Bumble, G. J. Clark, W. J. Galagher, A. Gupta, A. Kleinsasser, R. B. Laibowitz, R. D. Sandstrom, and M. R. Scheuermann, Physica C **153-155**, 1685 (1988).

APPENDIX 2

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OPTICAL RESPONSE OF EPITAXIAL AND GRANULAR FILMS OF $YBa_2Cu_3O_{7-\delta}$ AT TEMPERATURES FROM 25 K TO 100 K

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Abstract

We present the results of measurements of optical detection in epitaxial and granular films of $YBa_2Cu_3O_{7-\delta}$, at wavelengths of 0.63, 3.39, and 10.6 µm, at temperatures from 25 K to 100 K. Both types of film exhibit only bolometric detection, with no evidence for nonequilibrium effects in this temperature range. For 0.63 µm radiation, mechanically chopped at 725 Hz, measurements of a 10×90 µm epitaxial bridge yield a bolometric responsivity of approximately 4×10^3 V/W, and a detectivity D* of more than 10^8 cm√Hz/W. Granular films biased above their critical current are found to exhibit two-level switching noise, resulting in Lorentzian deviations from an otherwise "1/f" noise spectrum.

Introduction

Of the potential electronic applications for thin films of high temperature superconductors (HTS) their use as sensitive electromagnetic sensors is one of the most promising. Such applications include the use of HTS SQUID's, operating at liquid nitrogen temperatures and above, for geomagnetic surveying, and for biomedical applications. Such devices have been fabricated from granular films, with naturally occurring intergrain weak links, and from epitaxial films, with damaged areas serving as weak links.[1]

Another potential sensor application for HTS films is for broad-band optical detection. The most straightforward mode of operation for such a detector is the bolometric mode. Here the film is held in the middle of its transition, where the temperature derivative of the resistance, dR/dT, is large, and the incident radiation raises the temperature of the film and thus its resistance. Given a suitable current bias this resistance change is detected as a voltage signal. Bolometers made from low temperature superconductors have been studied extensively and have showed detectivities D* as high as 10^{12} cm√Hz/W.[2] However, the low operating temperature and slow response of such detectors make them noncompetitive with semiconductor detectors of comparable sensitivity.

An additional detection mechanism in superconducting films is the nonequilibrium mode, in which photons with energies above the gap break Cooper pairs, creating a *nonequilibrium* population of quasiparticles (as opposed to, for example, an equilibrium population characterized by a higher temperature). In a granular film, with strongly superconducting grains and weak intergrain Josephson coupling, this increase in the number of quasiparticles can lead to a measurable decrease in the critical currents of the intergrain weak links. A film biased at or above its critical current will thus exhibit a voltage increase upon irradiation, with the limiting time constant now of order the quasiparticle recombination time, which can be as short as 10^{-10} sec in a strong coupling superconductor.[3] Intergrain junctions arranged in series may contribute coherently to the signal, but incoherently to the noise, so that the signal to noise ratio will go as $1/\sqrt{N_s}$, where N_s is the number of junctions in series.[4]

Experimentally this mechanism can be traced to the pioneering work of Testardi on Pb films.[5] More recently this effect has been investigated in *granular* films of both low- and high-temperature superconductors, including $BaPb_{1-x}Bi_xO_3$,[4] NbN/BN,[6] and $YBa_2Cu_3O_{7-\delta}$ (YBCO).[7] The results of Enomoto *et al.* for $BaPb_{1-x}Bi_xO_3$ have been particularly promising, showing responsivities up to 10^4 V/W and D* = 3×10^{10} cm√Hz/W in a 10×10 µm microbridge detector.[4,8] The response time for this detector was fast, with optical response to chopped radiation being essentially independent of chopping frequency up to at least 0.7 GHz.[4]

Here we report the results of measurements of the optical response of both *epitaxial* and *granular* YBCO films, to both visible and infrared radiation.[9] While a granular film provides a more obvious realization of an array of weak links it is also possible that epitaxial films could contain an intrinsic weak link structure due to, for example, weakly coupled Cu-O planes, defects such as stacking faults,[10] or boundaries between single-crystal domains of different orientation. If this were the case then, in a sample of a given size, N_s might be much higher than in a granular film, making the signal larger for a given incident flux and improving the signal to noise ratio. In addition, epitaxial films have the advantage that they exhibit lower intrinsic noise than granular films, so that one can expect higher detectivity.

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Film Preparation

The fabrication procedure and details of film morphology for our epitaxial films have been reported elsewhere,[11] and only a brief summary will be given here. Films were deposited on single-crystal $SrTiO_3$ (100) and (110) substrates, by sequential magnetron sputtering from Y, Ba, and Cu sources, in oxygen partial pressures ranging from 3×10^{-6} to 3×10^{-4} torr, and were typically 0.35 µm thick. Annealing was performed in an atmosphere of oxygen, either entirely in-situ, or partially in-situ. In-situ annealed films were typically coated with 500 Å of gold, for contact purposes. The resulting films were epitaxial, with the c-axis in the film plane, and consisting of a random mosaic pattern of crystalline grains with perpendicular c axes. The films typically had T_c(onset) = 90 K, and T_c(R=0) = 35-80 K, depending on the deviations from stoichiometry and the details of the annealing schedule. Our optical studies have emphasized the use of relatively low T_c (35–60 K) films, in the belief that they should be more likely to contain intrinsic weak links.

Figure 1. Micrograph of a granular YBCO film on BaF_2/sapphire. The islands of needle-shaped grains are YBCO while the spherical grained material is a barium-rich phase, probably mostly BaF_2.

Granular films were produced under the same sputtering conditions, and were also typically 0.35 µm thick, the substrate in this case being sapphire with a 0.5 µm buffer layer of evaporated BaF_2. The buffer layer served to reduce reaction and interdiffusion of the YBCO and Al_2O_3, particularly the incorporation of Al into the superconductor, which leads to degraded film properties for films of thickness much less than 1 µm. Without the BaF_2 layer, 0.35 µm films were usually insulating after annealing, while those on buffer layers were superconducting, with T_c(onset) = 93 K, T_c(R=0) up to 70 K, and metallic resistivity above T_c.

Figure 1 shows a scanning electron micrograph of a granular film. The structure shows islands of needle-like grains, whose composition is close to 1:2:3 by EDS, separated by regions of a Ba-rich phase, probably mostly BaF_2, with small spherical grains. The latter regions are found to be transparent under an optical microscope while the former are opaque.

Films were patterned by conventional photolithography into microbridges from 10 to 200 µm wide. For samples with gold

overlayers the gold was first patterned by reactive ion etching, to form contact pads, and to define the area of the superconducting film which would be exposed to radiation. For all samples the YBCO pattern was then defined by Ar ion milling at 200 V. Using this process epitaxial films with linewidths as narrow as 10 μm could be produced with negligible degradation in superconducting properties. In contrast, granular films typically showed a T_c degradation of 10-20 K after patterning, even in 200 μm wide bridges.

Figure 2 shows an example of a granular detector produced in this manner. The broad lines on the left and right are the gold-coated current bias lines, while the narrower lines at the bottom are the voltage signal lines. The photosensitive area, in this case 50 μm × 100 μm, is at top center.

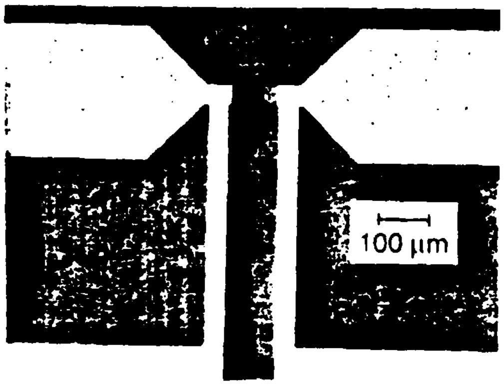

Figure 2. A granular detector sample, with gold-coated signal and bias lines. The 50 × 100 μm photosensitive area is at center top.

Critical Current vs. Magnetic Field

While the resistive transitions of the epitaxial and granular films are similar, differences in their properties are clearly evident in measurements of transport critical current, J_c, vs. magnetic field, H. For epitaxial films $J_c(H=0)$ at 4.2 K was typically 1–4 × 10^5 A/cm^2, consistent with transport along the c-direction in single crystals, while for granular films a typical figure was 200 A/cm^2. Figure 3 shows the results of measurements of $J_c(H)$ at 4.2 K, for a 25 μm wide epitaxial bridge (closed symbol) and a mechanically-scribed 1mm wide granular film (open symbol). The field was perpendicular to the film, and the voltage criterion used for defining J_c was 1 μV/cm. For the epitaxial film J_c exhibits a relatively slow H dependence, gradually decreasing to about a fourth of its zero-field value at 20 kOe. In contrast the granular film exhibits a sharp decrease in J_c at very low fields, dropping to one tenth of its zero-field value at only 100 Oe, and then decreasing more gradually at higher fields. The behavior of the granular film is quite close to that of bulk polycrystalline materials.[12]

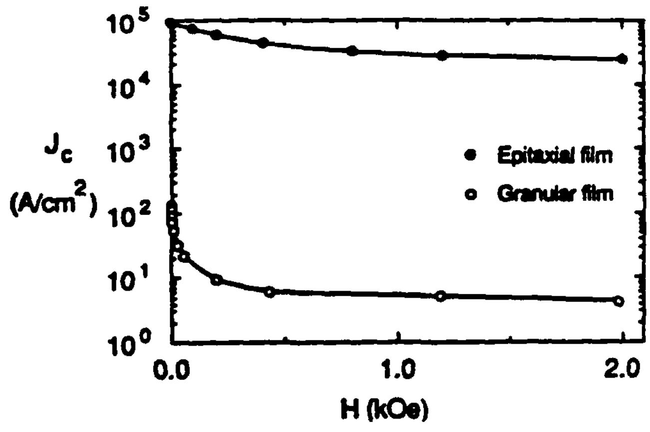

Figure 3. Transport critical current density vs. magnetic field at 4.2 K, for epitaxial (closed symbol) and granular (open symbol) films. The granular film shows a low J_c and strong field-dependence at low fields, indicating that its grains are weakly coupled.

These measurements reveal a strong difference between the intergrain coupling for epitaxial vs. granular films. The low value and strong field dependence of the transport J_c in the granular film suggests that the superconducting grains in such films are rather weakly coupled, as in a bulk material. Such a film should therefore be an ideal material in which to observe the nonequilibrium detection mode, which relies on the existence of weak links in the film. The epitaxial films, however, show strong intergrain coupling, and, at least in measurements of $J_c(H)$, no evidence for intrinsic weak link structure. This is consistent with the work of Koch *et al.* at IBM, where polycrystalline YBCO films (with weak intergrain coupling) patterned into dc SQUID's exhibited modulation of critical current vs. magnetic field, while epitaxial films did not. The difference was attributed to the presence of weak grain boundaries in the former case and their absence in the latter.[1]

Optical Response

For studies of optical response our radiation sources were HeNe lasers of wavelengths λ = 0.63 μm and 3.39 μm, and a CO_2 laser with λ = 10.6 μm. The laser beams were mechanically chopped, typically at frequencies from 10 Hz to several hundred Hz. Measurements were made in a closed-cycle refrigerator with base temperature 25 K.

Our experimental procedure was to bias the sample at a fixed current at or above its critical current, and observe the ac voltage response to radiation, δV, as a function of temperature, T, and bias current, I. The response of a 10 μm epitaxial bridge to 0.63 μm radiation, chopped at 725 Hz, is shown in Fig. 4(a), and exhibits two characteristic time scales. Upon turning on of the laser beam there is an initial "fast" rise in a time of order a microsecond, followed by a "slow" rise with time scale of order a millisecond. Figure 4(b) shows the response of a similar epitaxial sample to 10.6 μm radiation, and shows only a slow response, with time scale of order a millisecond. The response to 3.39 μm radiation is qualitatively similar to that at 10.6 μm, but with a time scale of several tenths of a second.

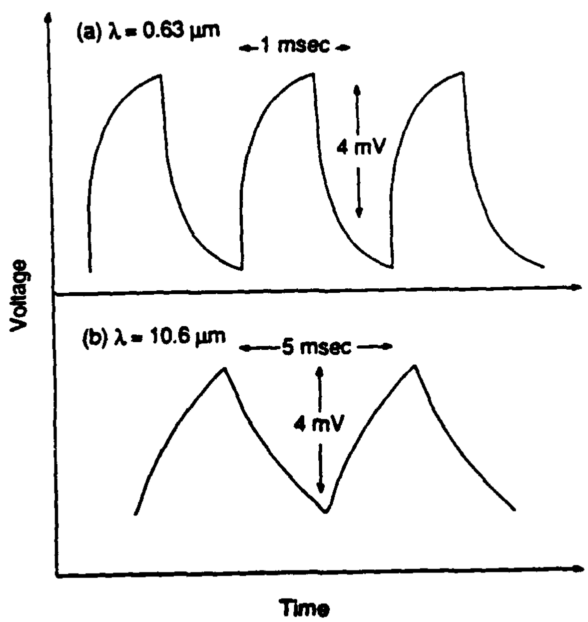

Figure 4. Real-time response of films to chopped radiation with (a) λ = 0.63 μm and (b) 10.6 μm. Granular and epitaxial films show almost identical behavior. The response at 0.63 μm shows "fast" (~ μsec) and "slow" (~ msec) components, while that at 10.6 μm shows only slow.

Figure 5 shows the temperature dependence of both "fast" and "slow" components of the response of Fig. 4(a), measured separately on an oscilloscope, for one sample at two different bias currents. Also shown for each current is the sample dc resistance vs. temperature, R(T), at that current. [Figure 5(a) also shows R(T) measured at low current for comparison]. The temperature

dependences of the fast and slow responses are similar, and for a given current both reach a maximum near the steepest portion of the R(T) curve measured at that current. The same temperature dependence was found for the responses to 3.39 μm and 10.6 μm radiation.

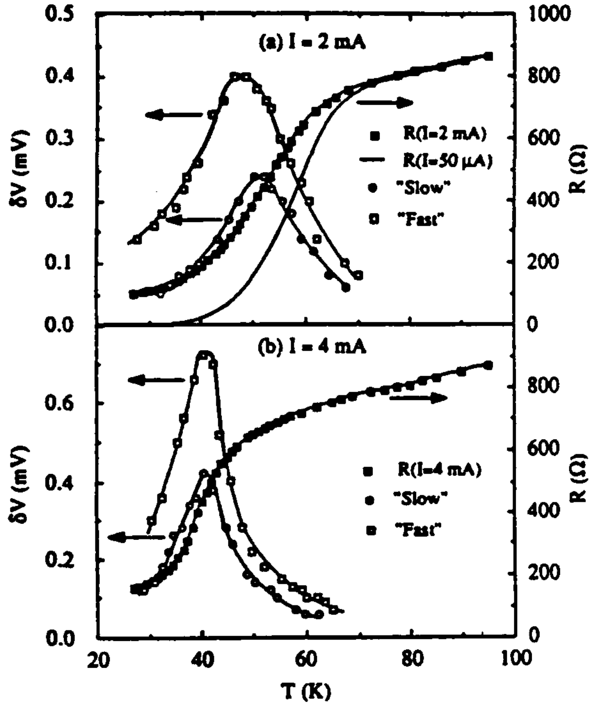

Figure 5. Temperature dependence of fast and slow responses, δV, of a 10 × 90 μm epitaxial bridge, for λ = 0.63 μm, at (a) I = 2 mA and (b) I = 4 mA, with corresponding R(T) curves. Both responses peak near the steepest part of the transition, independent of current, indicating that they are bolometric. Also shown in (a) is a low-current R(T) showing T_c = 35 K for this sample.

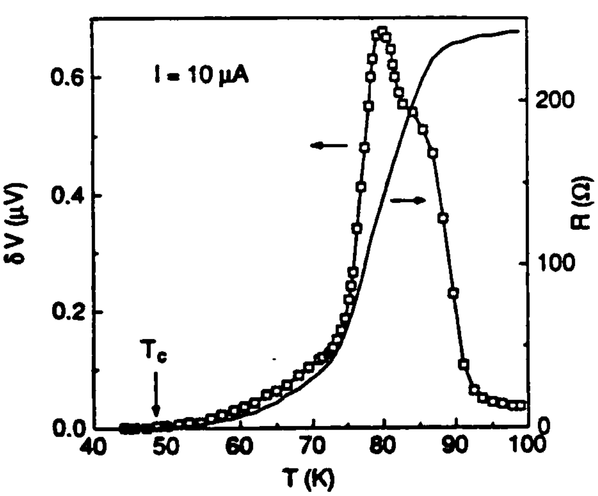

Figure 6. Similar to Fig. 5, but for a granular film measured at low current (I = 10 μA). Again the response is bolometric, peaking where dR/dT is largest, with no evidence for a peak at T_c(R=0).

Measurements made on granular films produce qualitatively similar results, with the maximum response again corresponding to the maximum in dR/dT, over a broad range of bias currents, and with similar response times. Figure 6, shows an example at low current, I = 10 μA, for a 200 × 200 μm granular sample, for 0.63 μm radiation, chopped at 725 Hz. Regardless of current level the temperature dependence of the response follows that of dR/dT, with no evidence for a peak in the response at T_c(R=0). This is in contrast to the results of Leung *et al.*, who found the maximum response at T_c(R=0) and only a weak bolometric response in the transition regime.[6]

The fact that the response to radiation has a maximum near where R(T) is steepest suggests that the observed response, for all wavelengths, is bolometric in origin. That is, the radiation is simply heating the sample and thereby increasing its dc resistance. The origin of the different time constants is currently unknown but may be due to the absorption of the various wavelengths by different portions of the film/substrate combination. For example, both $SrTiO_3$ and sapphire have transmission cutoffs at 6-7 μm, and thus will transmit 0.63 μm radiation not absorbed in the YBCO film, but absorb at 10.6 μm, contributing to a slow thermal response. The extremely long (tenths of seconds) time constant at 3.39 μm is particularly puzzling. It may, however, be necessary to take into account the absorption properties of a degraded surface layer on the YBCO, formed during exposure of the sample to the ambient atmosphere.

As for the sensitivity of the bolometric detection, one can clearly increase the responsivity by increasing the bias current, subject to the limitation that, at the same time, the optimal temperature will decrease, and both the power dissipated and the shot noise due to the bias current will increase. For samples with broad transitions, the relatively lower values of dR/dT are typically compensated by a higher sample resistivity, so that the resulting responsivities are similar, but with more power dissipated than in the higher-T_c, lower resistivity samples. We have measured responsivities, for the fast response above, as high as 4×10^3 V/W in a 10 × 90 μm epitaxial bridge. For 10.6 μm radiation, chopped at 200 Hz, responsivities were typically of order, 400 V/W.

From measurements of the sample noise we can estimate the detectivity, $D^* = (A \cdot \Delta f)^{1/2} \cdot (r/V_N)$, where A is the sample area, r the responsivity in volts per watt, V_N the rms noise voltage, and Δf the measurement bandwidth. For a 10 μm × 90 μm epitaxial detector with responsivity 4×10^3 V/W, noise measurements in a 100 Hz bandwidth at 1 kHz, yielded V_N = 1 μV, which gives $D^* = 10^8$ cm·Hz$^{1/2}$/W. Our value of D* is one hundred times larger than that reported for granular YBCO films,[7] but represents an intrinsically slower mechanism. Noise levels in our granular samples were typically an order of magnitude larger than in epitaxial samples at the same d.c. voltage, yielding correspondingly lower detectivities. Some preliminary details of noise spectroscopy in our granular films are discussed in the next section.

Noise in Granular Films

In the course of our optical measurements on granular films we have observed interesting noise phenomena of relevance to the application of granular HTS films. Specifically, we have observed two-level switching or "telegraph" noise in the d.c. voltage across a granular 200 μm bridge biased above its critical current, similar to that observed in single low-T_c tunnel junctions.[13] There the noise was attributed to the presence of localized electronic states in the tunnel barrier, which "trap" electrons, thereby modulating the barrier resistance on a quantum level.

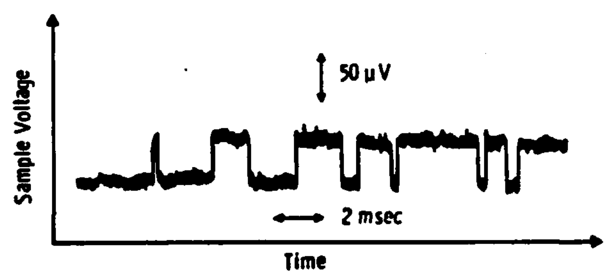

Figure 7. Two-level switching noise in the voltage of a 200 × 200 μm granular bridge biased in the resistive state at 232 mV.

Figure 7 shows a particularly clear example of such behavior, as observed directly on an oscilloscope with a bandwidth of 10 kHz. This behavior appears reproducibly within certain narrow windows of bias level, each sample having a characteristic set of such windows. Although our samples are *current* biased, measurements

as a function of both temperature and current, along with measurements of the current-voltage characteristics, reveal that these windows appear at fixed *voltage* levels, as was the case in the low-T_c tunnel junction studies.[13] We suggest that the origin of this noise is localized electronic states in the the various natural tunnel barriers between the superconducting grains.

Such a two-level fluctuator exhibits a Debye-Lorentz power spectrum of the form

$$S_v(f) \propto \frac{1}{1+(2\pi f \tau_{eff})^2} \quad , \qquad (1)$$

where $\tau_{eff} = \tau_1\tau_2/(\tau_1+\tau_2)$, τ_1 and τ_2 are the mean lifetimes for the two voltage states, and S_v is the noise power density. Measurements of the noise power density in the granular films reveal a generally "1/f" behavior, with deviations which can be well fitted to a sum of a limited number of such Lorentzians, with various values of τ_{eff}. Two examples are illustrated in Fig. 8, which shows data for one sample at two different voltage levels. The solid curves are fits incorporating a constant term, a 1/f background, plus five Lorentzians for the upper data, and two for the lower. The 1/f background may be attributed to further unresolved fluctuators of the form (1), or perhaps to another mechanism such as flux noise. As can be seen from the upper data in Fig. 8, a single such fluctuator can increase the noise power density by more than an order of magnitude above the 1/f background. Clearly, device operation at such an operating point is undesirable, and formation of intergrain barriers with fewer or no such localized states, such as normal metal barriers, will improve the noise characteristics of granular devices substantially.

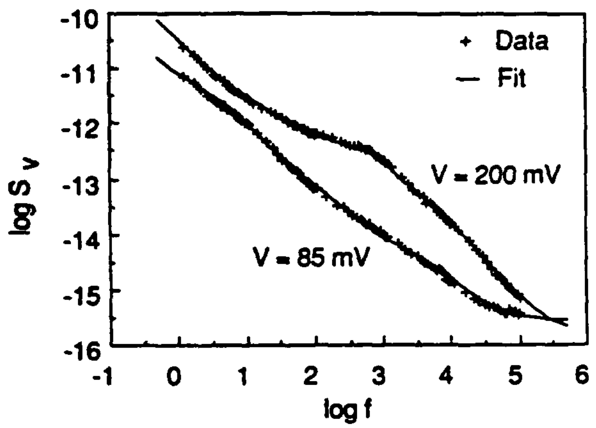

Figure 8. Noise power density, $S_v(f)$, in volts^2/Hz, for the same sample as Fig. 7, at two bias points. Deviations from a generally "1/f" behavior are well fit by a limited number of Lorentzians of the form (1). The solid lines are fits to a sum of a constant, a "1/f" term, plus five Lorentzians for the upper data and two for the lower.

Summary and Conclusions

Our measurements of the optical response of both epitaxial and granular YBCO films show only the bolometric detection mode, and no evidence for the nonequilibrium effect at temperatures from 25 K to above the onset of the superconducting transition. Although transport measurements of $J_c(H)$ in the granular films show that the grains in such films are weakly coupled, these weak links are not measurably affected by radiation in the visible through mid-IR. This is in disagreement with the results of Leung *et al.*, suggesting that there may be some fundamental difference between the weak links in their films and ours. Alternatively, the behavior of our granular films may be dominated by a small number of weak links, so few that the optical signal is unmeasurable. A third possibility is that the nonequilibrium effect may be seen only at lower temperatures than were accessible to us during this work.

Our future work will involve extending our measurements to 4.2 K, studies of granular films made by other non-vacuum ceramic techniques, and fabrication of better-characterized weak links in epitaxial films.

We are pleased to acknowledge the assistance of H. Buhay (film patterning), T. Mullen, and A. Karanovich (EDS). This work was supported by Air Force Office of Scientific Research / Strategic Defense Initiative Organization Contract No. F49620-88-C-0030.

References

[1] See for example, R. H. Koch, C. P. Umbach, M. M. Oprysko, J. D. Mannhart, B. Bumble, G. J. Clark, W. J. Gallagher, A. Gupta, A. Kleinsasser, R. B. Laibowitz, R. D. Sandstrom, and M. R. Scheuermann, "DC SQUIDS Made From $YBa_2Cu_3O_y$", Physica C, Vol. 153-155, pp. 1685–1689, 1988.

[2] K. Rose, C. L. Bertin, and R. M. Katz, in Applied Superconductivity, Vol. I, V. L. Newhouse ed., Academic Press Inc., New York, NY, 1975, Ch. 4, pp. 267–308.

[3] S. B. Kaplan, C. C. Chi, D. N. Langenberg, J. J. Chang, S. Jafarey, and D. J. Scalapino, "Quasiparticle and Phonon Lifetimes in Superconductors", Phys. Rev. B, Vol. 14, pp. 4854–4873, Dec. 1976.

[4] Y. Enomoto and T. Murakami, "Optical Detector Using Superconducting $BaPb_{0.7}Bi_{0.3}O_3$ Thin Films", J. Appl. Phys., Vol. 59, pp. 3807–3814, June 1986.

[5] L. R. Testardi, "Destruction of Superconductivity by Laser Light", Phys. Rev. B, Vol. 4, pp. 2189-2196, 1971.

[6] M. Leung, U. Strom, J. C. Culbertson, J. H. Claassen, S. A. Wolf, and R. W. Simon, "NbN/BN Granular Films - A Sensitive, High-Speed Detector For Pulsed Far-Infrared Radiation", Appl. Phys. Lett., Vol. 50, pp. 1691–1693, 1987.

[7] M. Leung, P. R. Broussard, J. H. Claassen, M. Osofsky, S. A. Wolf, and U. Strom, "Optical Detection in Thin Granular Films of Y-Ba-Cu-O at Temperatures Between 4.2 and 100 K", Appl. Phys. Lett., Vol. 51, pp. 2046–2047, 1987.

[8] P. L. Richards (private communication) has suggested that the detectivity claimed by Enomoto *et al.* is exaggerated, due to incorrect measurement of detector noise.

[9] A report of our results on epitaxial films is scheduled to appear in Appl. Phys. Lett., October 7, 1988.

[10] Y. Enomoto, T. Murakami, M. Suzuki, and K. Moriwaki, "Largely Anisotropic Superconducting Critical Current in Epitaxially Grown $Ba_2YCu_3O_{7-y}$ Thin Film", Jpn. J. Appl. Phys., Vol. 26, pp. L1248–1250 (1987).

[11] J. R. Gavaler, A. I. Braginski, J. Talvacchio, M. A. Janocko, M. G. Forrester, and J. Greggi, "Fabrication of High-T_c Superconducting $YBa_2Cu_3O_7$ Films", in High Temperature Superconductors II, D. W. Capone II, W. H. Butler, B. Batlogg, and C. W. Chu eds., Materials Research Society, Pittsburgh, 1988, pp. 193–196.

[12] J. W. Ekin, A. I. Braginski, A. J. Panson, M. A. Janocko, D. W. Capone II, N. J. Zaluzec, B. Flandermeyer, M. Hong, J. Kwo, S. H. Liou, and O. F. de Lima, "Evidence for Weak Link and Anisotropy Limitations on the Transport Critical Current in Bulk Polycrystalline $Y_1Ba_2Cu_3O_x$", J. Appl. Phys., Vol. 62, pp. 4821–4827, Dec. 1987.

[13] C. T. Rogers, R. A. Buhrman, W. J. Gallagher, S. I. Raider, A. W. Kleinsasser, and R. L. Sandstrom, "Electron Trap States and Low Frequency Noise in Tunnel Junctions", IEEE Trans. on Magn., Vol. MAG-23, pp.1658-1661 (1987).

APPENDIX 3

In Science and Technology of Thin-Film Superconductors
ed. by R. McConnell and S.A. Wolf
(Plenum, New York, 1989).

PHOTODETECTION WITH HIGH-T_c SUPERCONDUCTING FILMS

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INTRODUCTION

One of the promising applications of high-T_c superconducting thin films is the detection of infrared radiation. The purpose of this paper is to clarify which measurements are needed to identify the basic mechanism responsible for a photo-response, and to summarize the measurements made to date.

The motivation for studying high-T_c photodetectors stems largely from the results shown in Fig. 1. Figure 1 is a comparison of the detectivity, D^*, of two different superconducting Josephson junction detectors[1,2] with semiconductor detectors and D^* calculated for a 300 K background-limited photoconductor with a 180° field-of-view.[3] The shaded regions include data from 19 different semiconductor detectors.[3] Each semiconductor detector has a high D^* in a narrow wavelength range compared to the potentially broadband sensitivity of Josephson junction detectors.

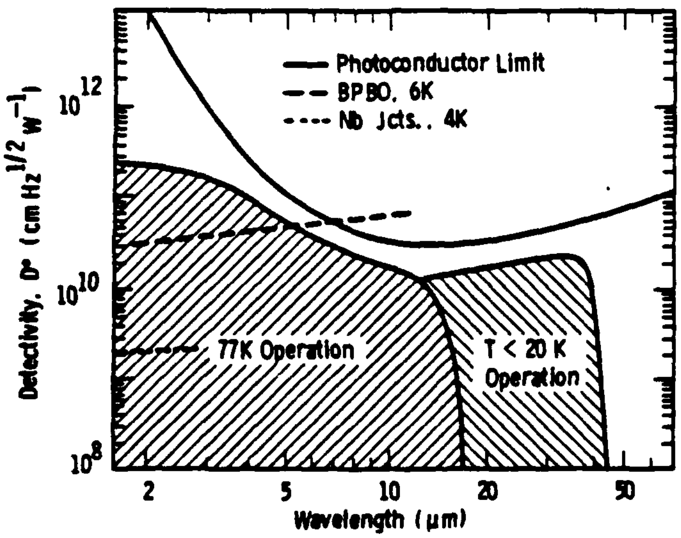


Fig. 1 - Detectivity of a granular $BaPb_{0.7}Bi_{0.3}O_3$ film measured at 6 K,[1] and discrete Nb tunnel junctions measured at 4.2 K,[2] compared with semiconductor detectors.[3]

In superconducting detectors exposed to radiation with energy greater than the gap energy, $\Delta(T)$, the absorbed radiation reduces the gap energy, modifying the current-voltage characteristics of Josephson junctions. Two possible mechanisms for gap-energy reduction will be considered here. The first is an equilibrium mechanism in which the film acts as a bolometer and the response is proportional to the temperature coefficient of resistance of a Josephson junction. The disadvantage of a bolometer is that the response is slow unless the amplitude of the response is traded off for efficient cooling. The second mechanism is dependent on the creation of quasiparticle pairs by the incident radiation. This non-equilibrium quasiparticle density is measured in Josephson junction I-V curves as a reduced gap energy. The response time of the non-equilibrium mechanism is determined by the quasiparticle recombination time – as short as 10^{-10} s in a strong-coupling superconductor at $T \simeq T_c$.[4]

The data from superconducting detectors shown in Fig. 1 were measured in detectors composed of different types of Josephson junctions. The lower D^* data is from a $Nb/Al_2O_3/Nb$ Josephson tunnel junction.[2] The response at 4.2 K was attributed to a bolometric effect since it decreased by approximately three orders of magnitude when the sample was measured in superfluid helium at 2 K. The $BaPb_{0.7}Bi_{0.3}O_3$ (BPBO) detectors were granular films which had grain-boundary Josephson junctions with I-V characteristics similar to point-contact or microbridge junctions.[1] These detectors not only had very high D^* values, but had response times on the order of 1 ns – attributed to a non-equilibrium response mechanism. Three of the important properties of BPBO which contributed to the detector results are also present in high-T_c oxide superconductors, typified by $YBa_2Cu_3O_7$ (YBCO).

1. Both BPBO[1] and YBCO[5] have higher absorption and lower reflection coefficients than transition metal superconductors due to their lower density of electronic states.
2. The decrease in gap energy due to an excess quasiparticle density is inversely related to the density of states and is, therefore, greater in the oxide superconductors.
3. Grain-boundary Josephson junctions are readily formed in the oxide superconductors. A higher density of junctions can be realized in granular films than with discrete microbridge junctions lithographically defined. Tunnel junctions of these materials have not been made due to their short coherence lengths, unstable surfaces, and high processing temperatures.

SIMULATED RESPONSES TO RADIATION

This section will present the results of simple models for the bolometric and non-equilibrium responsivities, r_B and r_{NE}, of granular films modeled as microbridge Josephson junctions connected in series. The responsivity will be considered as a function of bias current, I_B, and reduced temperature, $t = T/T_c$. The important results – those which are neither obvious without invoking a model nor overly model-dependent – should clarify which characteristic forms of the responsivity are useful in identifying equilibrium and non-equilibrium response mechanisms.

The series arrays used in this model each consisted of 100 junctions with critical currents at $T = 0$ which had a Gaussian distribution centered at $I_{c\text{-avg}}$ and standard deviation, σ, expressed as a percentage of $I_{c\text{-avg}}$. No junctions were permitted to have a critical current in the "tails" of the distribution, that is, less than zero or greater than $2I_{c\text{-avg}}$. The resistance at currents much greater than the critical current, R_n, was assumed to be the same for each junction and independent of temperature. The particular distribution chosen for R_n was not an important assumption. However, the

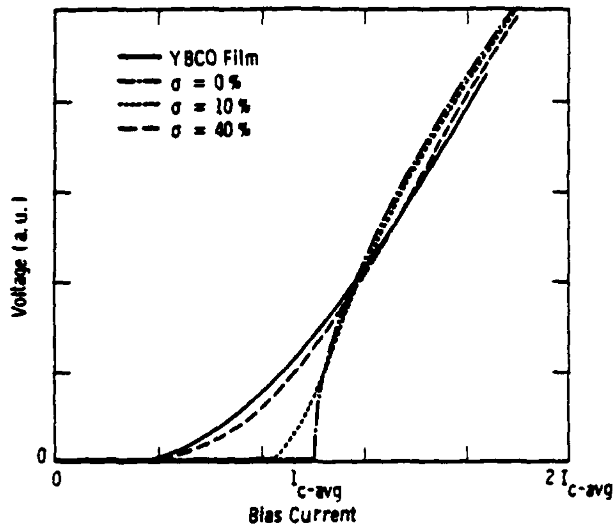


Fig. 2 - Calculated I-V curves for three series arrays with σ = 0, 10, and 40%, and the I-V curve of a bridge patterned in a YBCO film. The critical current of the bridge at T = 30 K was 0.25 mA and its resistance at 1 mA was 45 Ω.

assumption of temperature independence for R_n will give a poor simulation of those superconducting films which exhibit strongly semiconducting behavior of resistivity for $T > T_c$. The $t = 0$ I-V curves for these series arrays were calculated in the RSJ model[6] and are shown in Fig. 2. The I-V curve of a 10 μm wide by 90 μm long bridge patterned in a sputtered YBCO film is also shown in Fig. 2 for comparison of the model I-V curves with that of a film for which photo-response data has been published.[7]

The general form of the bolometric and non-equilibrium responsivities is given below for a single current-biased junction where Φ is the incident photon flux in W/cm^2, I_B is the bias current, I_c is the temperature-dependent Josephson critical current, and n_q is the quasiparticle density. The only approximation made in Equs. 1 and 2 is that R_n is independent of temperature. Note that the responsivity is expressed in units of V-cm^2/W – in agreement with Ref. 2 – since the response, δV,* is independent of detector area for a fixed photon flux for either mechanism.

$$r_B = \frac{\delta V}{\delta \Phi} = I_B \left.\frac{\partial R}{\partial T}\right|_{I_B} \frac{\delta T}{\delta \Phi} \simeq \left.\frac{\partial V}{\partial I_c}\right|_{I_B} \frac{dI_c}{dT}\frac{\delta T}{\delta \Phi} \tag{1}$$

$$r_{NE} = \frac{\delta V}{\delta \Phi} \simeq \left.\frac{\partial V}{\partial I_c}\right|_{I_B} \left.\frac{\partial I_c}{\partial \Delta}\right|_T \left.\frac{\partial \Delta}{\partial n_q}\right|_T \frac{\delta n_q}{\delta \Phi} \tag{2}$$

* The bolometric response, $\delta V = r_B\, \delta\Phi = I_B\, \partial R/\partial T\, \delta T$, where bridge resistance, R, is independent of area for a fixed aspect ratio, δT is independent of area for a fixed ratio of cooling area to detection area, and I_B is assumed to be adjusted for maximum response.

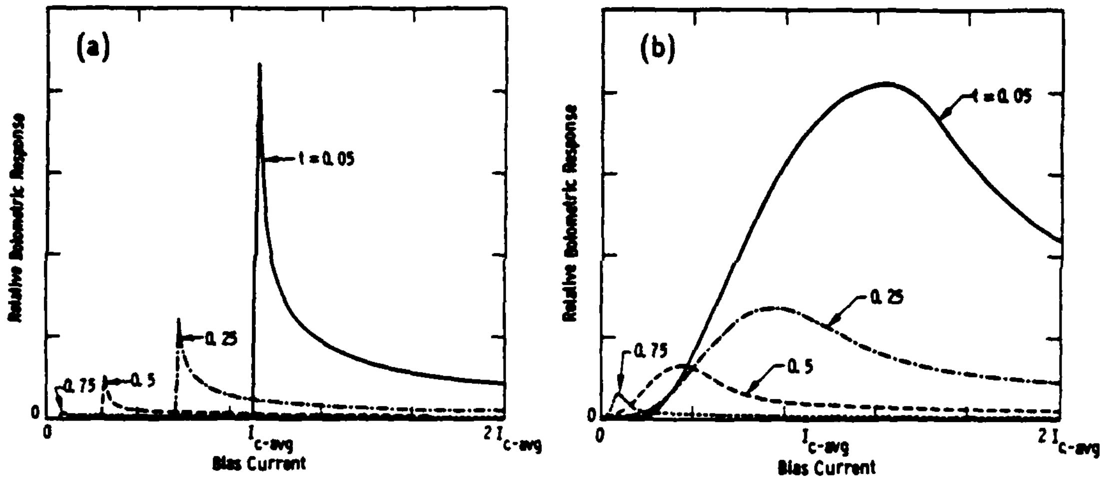


Fig. 3 - The simulated bolometric response of junction arrays with (a) $\sigma = 0$, and (b) $\sigma = 40\%$ for reduced temperatures of 0.05, 0.25, 0.5, and 0.75. The discontinuities in (a) at $I_B = I_c(T)$ were rounded by the discrete nature of the calculation.

The only factor in Equs. 1 and 2 that depends on I_B is $\partial V/\partial I_c$, and it appears in each equation. Therefore, the general shape of measured photoresponse plotted as a function of bias current cannot be used to distinguish which response mechanism is dominant. Simulated curves of *response versus* bias current are plotted in Figs. 3(a) and (b) for series junctions with $\sigma = 0$ and 40%, respectively, using $\partial V/\partial I_c$ calculated from the RSJ model. The qualitative features of $\delta V(I_B)$ data published in Refs. 1, 8, and 9, are present in the curves in Fig. 3.

In contrast to the effects of changing bias current, the effect of changing temperature is completely different in Equs. 1 and 2. The temperature dependence of $\partial V/\partial I_c$ is described by $I_c(T)$. The following relationships were used in the simulations for $I_c(T,\Delta)$ and δn_q:

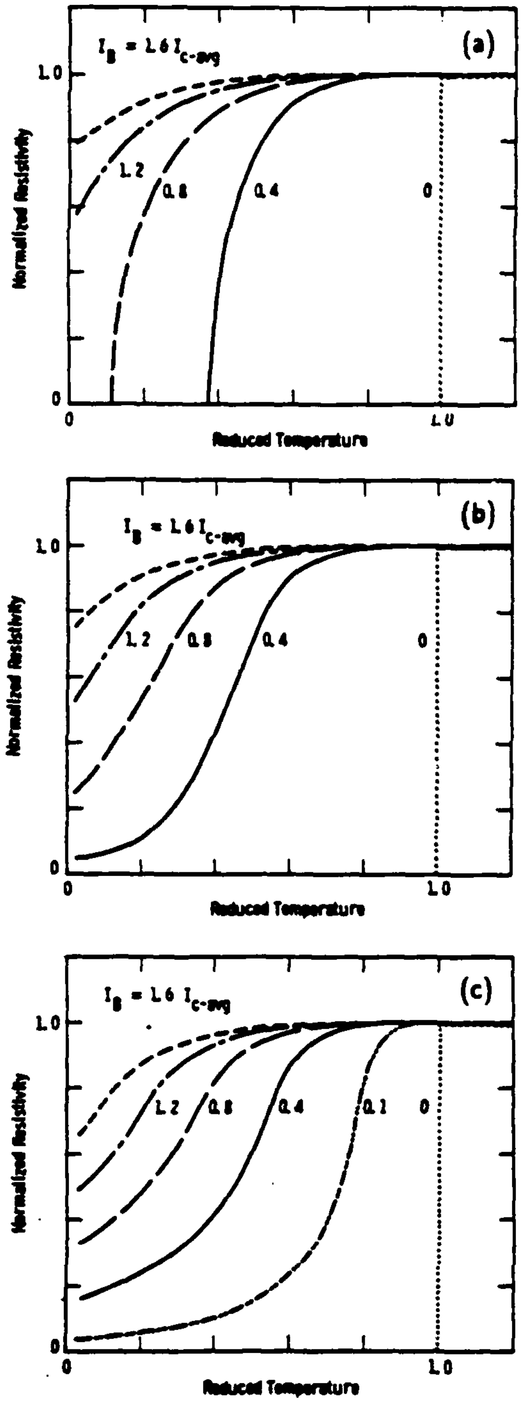
$$I_c \propto (1-t)^2 \qquad \text{(Ref. 10)} \qquad (3)$$

$$\frac{\partial I_c}{\partial \Delta} \propto (1-t)^{1/2} \qquad \text{(Ref. 11)} \qquad (4)$$

$$\delta n_q(T) \propto \tau_{eff}(T) \propto t^{-1/2}\, e^{\Delta(0)/kT} \simeq t^{-1/2}\, e^{1.76/t} \qquad (5)$$

where τ_{eff} is an effective quasiparticle recombination time.[12] The effective lifetime was assumed to have the same dependence as the simple recombination time,[4] and a weak coupling BCS relationship was assumed for $\Delta(0)/kT_c$. Following Ref. 1, $\partial\Delta/\partial n_q$ was taken as a constant − an appropriate assumption for δn_q small compared to the equilibrium quasiparticle density.

The only temperature dependence which has not been specified at this point is that of the change in temperature of a bolometer, $\delta T = P/(KA/d)$, where − for a particular bridge of area, $A = 10\times90\ \mu m^2$ − $P \simeq 0.6\ \mu W$ was the laser power incident on the bridge,[14] and K(T) was the thermal



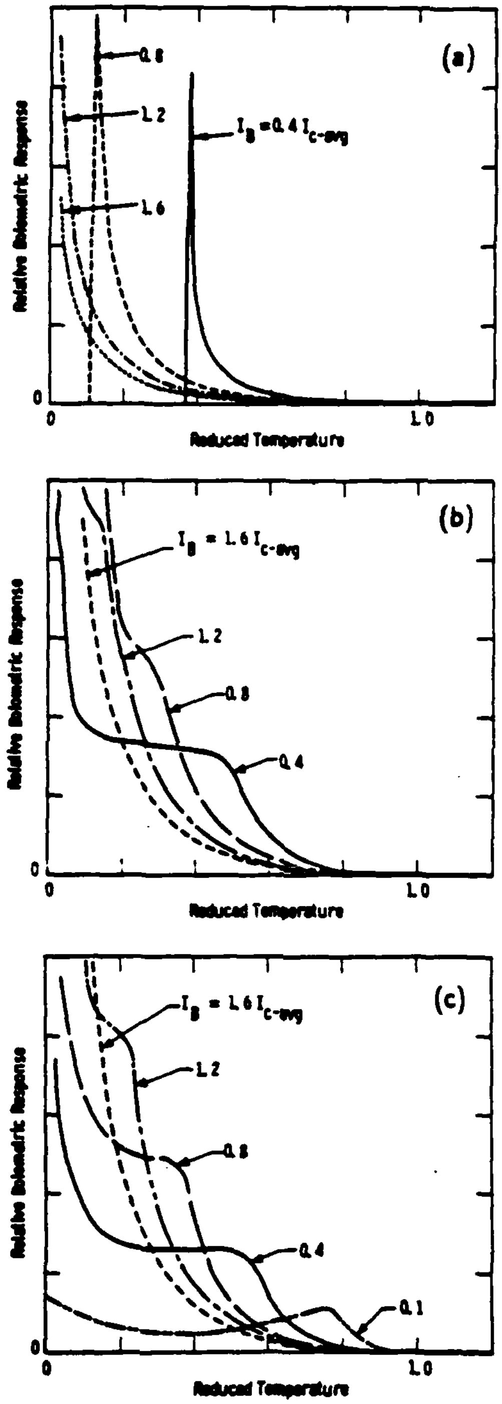


Fig. 4 - Calculations of resistance plotted for various values of the bias current as a function of temperature for series arrays with σ = (a) 0, (b) 40, and (c) 90%.

Fig. 5 - Calculations of bolometric response plotted for various values of the bias current as a function of temperature for series arrays with σ = (a) 0, (b) 40, and (c) 90%.

conductivity of the thermal barrier of thickness, d. The temperature rise was estimated to be 10 mK from the slope of V(T) measured at constant bias current. The thermal barrier was assumed to be a degraded film layer ~100 nm thick which is known to exist adjacent to the interface with the substrate.[15] The thermal conductivity calculated from δT and P, K $\simeq$ 10^{-4} W/cm/K, is the same order of magnitude as that of oxygen-deficient, tetragonal YBCO.[13] The temperature dependence of the thermal conductivity of tetragonal YBCO, $K(T) \propto t^{1/2}$,[13] was used in our model of photoresponse.

Since K varies slowly at high temperature ($t > 0.5$), the bolometric response follows the temperature derivative of $R(I_B,T)$ as $T \rightarrow T_c$. Figure 4 contains a series of calculated $R(I_B,T)$ curves for three series arrays with σ = 0, 40, and 90%. The curves in Fig. 4 show that an infinitely sharp transition to the superconducting state has been assumed (for small I_B) and that the transition appeared to broaden as the bias current was increased. The most significant feature of the curves in Fig. 4 was that – depending on σ and I_B – the largest value of dR/dT was found anywhere from $T = 0$ (Fig. 4(a), $I_B \geq I_{c\text{-avg}}$) to a temperature approaching T_c (Fig. 4(c), $I_B = 0.1\ I_{c\text{-avg}}$). The temperature dependence of the bolometric response is shown in Fig. 5 for the same three series arrays. The most significant feature in Fig. 5 is the appearance of a peak in the response near T_c coupled with a rising value of the response as the temperature is reduced to $<0.1T_c$.

The calculated temperature dependence of the non-equilibrium response is shown on a linear scale in Fig. 6(a) and on a logarithmic scale in Fig. 6(b). The results in Fig. 6 were calculated for junctions with σ = 10% but are representative of simulations performed with distributions with $0 \leq \sigma < 100\%$. The curve for $I_B/I_{c\text{-avg}} = 0.4$ had zero response at low temperatures since $\partial V/\partial I_c = 0$ for $I_B < I_c(T)$. However, for any detector biased at a current greater than the critical current, the exponential temperature dependence of effective quasiparticle lifetime dominated the response. A comparison of the calculations for bolometric and non-equilibrium responses shown in Figs. 5 and 6 indicate that measurements at low temperatures can be used to increase the possibility of observing the latter type of response. However, the large values of τ_{eff} expected at these low temperatures could make it impossible to distinguish the two effects on the basis of response time.

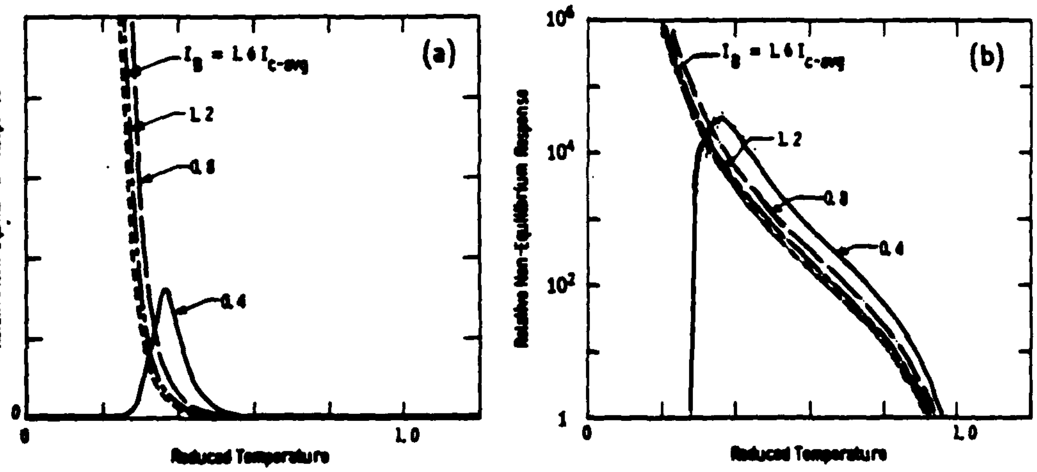


Fig. 6 - The calculated non-equilibrium response plotted on (a) a linear and (b) a logarithmic scale for various values of the bias current for a series of junctions with σ = 10%.

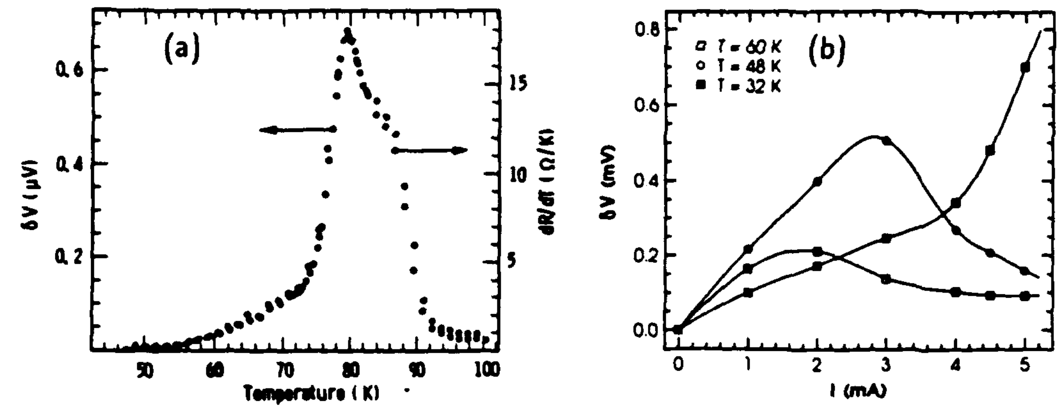


Fig. 7 - (a) A comparison of measurements of dR/dT and the response of a YBCO detector to 10.6 μm radiation which indicates that the response is purely bolometric. (b) Measured photo-response plotted as a function of bias current for a YBCO detector held at various temperatures.

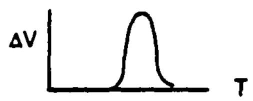
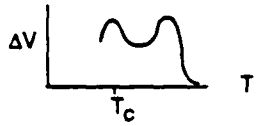
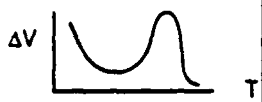
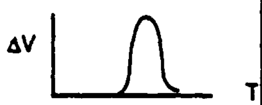
DISCUSSION OF EXPERIMENTAL RESULTS

With the exception of one report on the response of $LaSr_{1-x}Cu_xO_4$,[16] YBCO films have been used for all photodetection measurements with high-T_c films. Figure 7 shows response data which is typical of YBCO samples thought to have a purely bolometric response. The data in Fig. 7(a) is from a granular YBCO film sputtered onto a BaF_2 buffer layer as described in Ref. 14, and is a comparison showing close agreement between the temperature dependence of dR/dT and photo-response. A comparison of Fig. 7(a) with Fig. 5 shows that the model series array with the broadest distribution and biased at low I_B (Fig. 5(c); σ = 90%) had a peak in the response at high reduced temperatures in agreement with the experimental results. However, the correlation between measured response and dR/dT was better than indicated by Equ. 1 or Figs. 4 and 5. The difference is that the thermal conductivity was modeled as $K(T) \propto t^{1/2}$ and the thermal conductance of the measured detector apparently varied more slowly than that in the vicinity of T_c. The interface layer between the high-T_c film and the substrate was modeled as tetragonal $YBa_2Cu_3O_6$, but certainly consisted of other oxides as well – especially BaO.[15] The important aspect of the temperature dependence of K is not the detailed dependence near T_c, but the fact that, in simulations, K(T) led to a rising response as the temperature was decreased $<<T_c$. Equally important, although not considered in the steady-state model, is that K(T) affects the time response of a bolometric δV measured at various temperatures.

Fig. 7(b) shows the dependence of photo-response on bias current for a detector which behaved as a bolometer based on the measurements of response versus temperature and time presented in Ref. 7. In contrast to the conclusions of Ref. 9, the presence of a peak in $\delta V(I_B)$ is not inconsistent with a bolometric response. The peak is consistent with the calculated curves of Fig. 3(b) and the discussion of Equs. 1 and 2.

A summary of published photo-response measurements is presented in Table 1. Since the dependence of response on bias current does not help to identify the detection mechanism, only the temperature and temporal dependences are included. The temperature dependence is indicated by a sketch of $\delta V(T)$. The temporal dependence is indicated by the measured

Table 1 - Summary of reported infrared responses of YBCO films.

Reference	Temperature dependence	Temporal response	Possible mechanism, sensitivity
Forrester et al. (14)		τ = μsec– 0.1 sec	Bolometric $r = 4 \times 10^3$ V/W $D^* = 10^8$ cm√Hz/W
Strom et al. (19)		$\sim \omega^{-1/2}$	Bolometric + "Optically induced flux flow" $D^* = 10^7$
Osterman et al. (9)		τ <0.25 msec	Bolometric + nonequilibrium? at 1.8 K $r = 0.01$ V/(W/cm^2)
Wilson et al. (8)		τ < 0.1 msec	Bolometric + nonequilibrium? $r = 3000$ V/W $D^* = 5 \times 10^7$
Enomoto et al. (20)	?	$\sim \omega^{-1/2}$	Bolometric $r = 10$ V/W (@ 10 kHz)
Brocklesby et al. (21)		"On" = 10 –100 ns	Bolometric $r \sim 0.1$ V/W

response time, the maximum response time with a limit determined by measurement apparatus, or the dependence of δV on the frequency at which incident radiation was chopped. Some reports of bolometric responses[17,18] were excluded from Table 1 since such data is adequately represented and typical data are shown in Fig. 7.

The most interesting data in Table 1 are the points measured at low temperature by Osterman et al.[9] and Wilson et al.[8] Although the time response is unknown for this data, even a slow response (>>μsec) would not rule out the non-equilibrium detection mechanism since recombination times should be long as $T \to 0$. With the temperature dependence as the only remaining guide, the low-temperature data of Ref. 8 can be explained as the effect of K(T) on a bolometric response. The change of response with temperature is not exponential as predicted by the non-equilibrium model. The single low-temperature data point of Ref. 9 was measured with the sample immersed in superfluid helium to increase K(T) and minimize a bolometric response. Additional measurements made with small changes in the helium bath temperature could be sufficient to identify the detection mechanism.

The response data from Ref. 19 is noteworthy in that a second peak in the response was measured at a temperature (~25K) where the slope of R(T)

was not a maximum. The response was relatively slow and decreased as $\sim\omega^{-1/2}$ for kHz frequencies. Measurements of the response time as a function of temperature could be used to identify the non-equilibrium mechanism considered in this paper.

SUMMARY AND CONCLUSIONS

The issue of which response mechanism is active in the detection of infrared radiation by high-T_c films does not have a direct bearing on their potential usefulness. The response of any detector simply needs to be large enough to raise the level of the detector noise higher than that of other noise sources in the system, and fast enough for the particular application at hand. For most applications, a bolometric (equilibrium) response is inadequate to meet these two needs simultaneously, but a non-equilibrium detection mechanism has not been unambiguously observed in high-T_c superconducting films. Measurements of peaks in δV versus bias current and increases in δV at low temperatures are not sufficient indicators of a non-equilibrium response. Both the temperature and time dependence of the response of a non-equilibrium detector are expected to be dominated by the exponential temperature dependence of effective recombination times for quasiparticles. Therefore, the two most convincing tests for establishing that a non-equilibrium detection mechanism is active are response measurements which show:

1. An exponentially increasing magnitude of response as the temperature is decreased.
2. An exponentially increasing response time as the temperature is decreased.

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REFERENCES

1. Y. Enomoto and T. Murakami, "Optical Detector Using Superconducting $BaPb_{0.7}Bi_{0.3}O_3$," J. Appl. Phys. 59, 3808 (1986), and Y. Enomoto, T. Murakami, and M. Suzuki, "Infrared Optical Detector Using Superconducting Oxide Thin Film," Physica C 153-155, 1592 (1988).
2. D. P. Osterman, M. Radparvar, and S. M. Faris, "Optical Detection by Suppression of the Gap Voltage in Niobium Junctions," to be published in IEEE Trans. Magn. MAG-25 (1989).
3. W. L. Wolfe and G. J. Zissis, eds., The Infrared Handbook (Office of Naval Research, Washington, 1978), p.-11-87.
4. S. B. Kaplan, C. C. Chi, D. N. Langenberg, J. J. Chang, S. Jafarey, and D. J. Scalapino, "Quasiparticle and Phonon Lifetimes in Superconductors," Phys. Rev. B 14, 4854 (1976).
5. I. Bozovic, K. Char, S. J. B. Yoo, A. Kapitulnik, M. R. Beasley, T. H. Geballe, Z. Z. Wang, S. Hagen, N. P. Ong, D. E. Aspnes, and M. K. Kelly, "Optical Anisotropy of $YBa_2Cu_3O_{7-x}$," Phys. Rev. B 38(7), 5077 (1988).
6. L. G. Aslamazoff and A. I. Larkin, "Josephson effect in Superconducting Point Contacts," JETP Lett. 9, 87 (1969).
7. M. G. Forrester, M. Gottlieb, J. R. Gavaler, and A. I. Braginski, "Optical Response of Epitaxial Films of $YBa_2Cu_3O_{7-\delta}$," Appl. Phys. Lett. 53(14), 1332 (1988).
8. J. A. Wilson, J. M. Myrosznyk, R. E. Kvass, M. D. Jack, P. R. Norton, A. H. Hamdi, J. V. Mantese, A. L. Micheli, J. Y. Josefowicz,

A. T. Hunter, and D.B. Rensch, "IR Detection in Superconducting YBaCuO," paper A2, presented Mtg. IRIS Specialty Group on Infrared Detectors, Baltimore, August 1988.
9. D. P. Osterman, R. Drake, R. Patt, E. K. Track, M. Radparvar, and S. M. Faris, "Optical Response of YBCO Thin Films and Weak-Links," to be published in IEEE Trans. Magn. MAG-25 (1989).
10. K. Moriwaki, Y. Enomoto, and T. Murakami, "Josephson Junctions Observed in $La_{1.8}Sr_{0.2}CuO_4$ Superconducting Polycrystalline-Films," Jpn. J. Appl. Phys. 26(4), 521 (1987).
11. This is a simplification based on K. K. Likharev, "Superconducting Weak Links," Rev. Mod. Phys. 51, 116 (1979).
12. A. Rothwarf and B. N. Taylor, "Measurement of Recombination Lifetimes in Superconductors," Phys. Rev. Lett. 19, 27 (1966).
13. J. Heremans, D. T. Morelli, G. W. Smith, and S. C. Strite III, "Thermal and Electronic Properties of Rare-Earth $Ba_2Cu_3O_x$ Superconductors," Phys. Rev. B 37(4), 1604-1610 (1988).
14. M. G. Forrester, M. Gottlieb, J. R. Gavaler, and A. I. Braginski, "Optical Response of Epitaxial and Granular Films of $YBa_2Cu_3O_{7-\delta}$ at Temperatures from 25K to 100K," to be published in IEEE Trans. Magn. MAG-25, (1989).
15. J. Talvacchio, J. R. Gavaler, and J. Greggi, "Comparison of $YBa_2Cu_3O_7$ Films Grown by Solid-State and Vapor-Phase Epitaxy," to be published in IEEE Trans. Magn. MAG-25, (1989).
16. K. Moriwaki, Y. Enomoto, and T. Murakami, "I-V Characteristics of $(La_{1-x}Sr_x)_2CuO_4$ Superconducting Films and Infrared Irradiation Effects," Jpn. J. Appl. Phys. Suppl. 26-3, 1147 (1987).
17. P. L. Richards, S. Verghese, T. H. Geballe, and S. R. Spielman, "The High T_c Superconducting Bolometer," to be published in IEEE Trans. Magn. MAG-25, (1989).
18. F. H. Garzon, "Fabrication of Infrared Detectors Based on Granular Thin Films of $YBa_2Cu_3O_7$," presented 174th Electrochem. Soc. Mtg., Chicago, 1988.
19. U. Strom, E. S. Snow, R. L. Henry, P. R. Broussard, J. H. Claassen, and S. A. Wolf, "Photoconductive Response of Granular Superconducting Films," to be published in IEEE Trans. Magn. MAG-25, (1989), and U. Strom, E. S. Snow, M. Leung, P. R. Broussard, J. H. Claassen, and S. A. Wolf, "Optical Response of Granular Superconducting Films of Y-Ba-Cu-O and NbN/BN," SPIE Proceedings Vol. 948, High-T_c Superconductivity: Thin Films and Devices, edited by R. B. van Dover and C. C. Chi (SPIE, Bellingham, Washington, 1988), p. 10. Temporal dependence data obtained from M. Leung, private communication.
20. Y. Enomoto, T. Murakami, and M. Suzuki, "Infrared Optical Detector Using Superconducting Oxide Thin Film," Proc. 5th Intl. Workshop on Future Electron Devices (Miyagi-Zao, 1988), p. 325.
21. W. S. Brocklesby, D. Monroe, A. F. J. Levi, M. Hong, S. H. Liou, J. Kwo, and C. E. Rice, "Electrical Response of Superconducting $YBa_2Cu_3O_{7-\delta}$ to Light," preprint, 1988.